Center for Advanced Computation

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
URBANA, ILLINOIS 61801

THE COAL FUTURE

APPENDIX F

Coal Transportation:
Unit Trains - Slurry
and Pneumatic Pipelines

Appendix F

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Final Report

The Coal Future: Economic and Technological Analysis of Initiatives and Innovations to Secure Fuel Supply Independence

by

Michael Rieber
Center for Advanced Computation
University of Illinois at Urbana-Champaign

and

Shao Lee Soo
James Stukel
College of Engineering
University of Illinois at Urbana-Champaign

Advisor
Jack Simon, Chief
Illinois State Geological Survey

Center for Advanced Computation
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

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APPENDIX F

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Unit Trains - Slurry and Pneumatic Pipelines

Contents

COST OF TRANSPORTATION OF COAL: RAIL vs SLURRY PIPELINE

S. L. Soo and L. Ballard

Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois

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FOREWORD

This study, supported by NSF (RANN), analyzes the relationship between current long distance coal transport technology and national coal supply. Our findings confirm those made elsewhere that, when new railroad is to be built (even if only 40 percent of the total distance), a slurry pipeline may have a cost advantage (¢/ton-mile) of as much as two to one. Yet, water requirements and the results of a possible line break or loss of power are still unsolved environmental impact problems. However, where roadbed is already available, even if the most elaborate upgrading is required to sustain a minimum loaded train speed of 50 mph (80 kmph), the resultant transportation cost is only one-half that of a new slurry pipeline. This result, together with the availability of the rail for other types of shipment and a further decrease in coal transport costs if the rail is served by a pneumatic pipeline system for gathering and distribution, rules out replacing existing railroad by slurry pipelines. Where railroad is nonexistent, and for long distances, a pneumatic pipeline will become competitive with a slurry pipeline.

A cost distribution shows that the slurry pipeline is capital intensive while a railroad (upgraded to 50 mph (80 kmph) loaded) remains skilled labor intensive. For example, railroad equipment utilizes one-half of the steel tonnage of a slurry pipeline. Furthermore, the building of elements of a rail system is labor intensive and, therefore, contributes to employment in the years to come.

Abandoning a railroad in favor of a slurry pipeline, such as the one proposed for shipment from Wyoming to Arkansas, would be a wasteful policy error. Our recommendations include identification of coal shipping railroads for upgrading and federal expenditures to study the alternative economic and social impacts.

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INTRODUCTION

Among the options for coal transportation, existing technology offers the choice of rail or unit trains and slurry pipelines. Pneumatic pipelines offer another option [1]*; however, this technology for the shipment of comparable tonnage is presently incomplete and is more suitable for programs in the near future. This presentation concerns the immediate coal transport needs and how they can be met. Among the available options are new slurry pipelines and new rails or upgrading existing rails in various degrees for unit train shipment. As corollaries, we shall consider the economic impact of a choice in terms of direct employment, investment, indirect employment via manufacturing opportunities, and long range societal benefits of each program. Also of concern is the selection of routes and their relation to the economic and technological interrelations.

National coal shipments were 0.63 billion tons per year (bty) (or 0.57 billion metric tons per year (bmty)) in 1947, fell to 0.45 bty (0.41 bmty) in the late 1960's, and increased again to 0.63 bty (0.57 bmty) in 1974. The production estimate for 1985 is 1.2 to 1.5 bty (1.1 to 1.4 bmty) [2]. The ability to triple the amount of coal shipped must be found. An estimated capital outlay of $21 billion by 1985 will be required. The accuracy of the estimates are dependent on the logistics of supply and the trend of technology. The tripling is not expected to be uniform; for example, coal gasification might take 30 to 40 percent of the coal produced, and regional concentration is expected. Alternatively, the estimated 50-50 distribution of surface and underground coal production might be altered [2]. Much of the currently planned eastward shipment of low sulfur western coal [2] will be modified significantly by any gasification processes which can

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*Numbers in brackets refer to entries in REFERENCES.

successfully handle high sulfur Illinois coal. Moreover, any predictions should include estimates of technological evolutions.

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PART I: UNIT TRAINS

Economical and efficient transportation of coal must be available in conjunction with the anticipated increase in mine production to meet U.S. energy needs. A report prepared by the Task Force on Energy of the National Academy of Engineering, after concluding that the 1973 coal production rate of 600 million tons per year (540 million metric tons) could be doubled to at least 1,260 million (1,140 million metric tons) by 1985, said [2]:

> "There are serious barriers to increased coal production, principally transport. More unit trains, new slurry and gas pipelines, and enlarged capacities for the nation's inland waterway systems would be needed to transport as much as 660 million tons per year (600 million metric tons) of additional coal."

A data base of unit train costs has been developed for comparison with other coal transport options. These costs are significant because unit train tariffs charged by railroad lines do not necessarily reflect the actual costs of unit train shipments. This is especially true for large shipments. A computer model for unit train component costs developed by Ferguson [4] was used to calculate unit train costs.

COMPARISON AND JUSTIFICATION OF MODEL

To test the accuracy of the computer model, it was used to compute costs for current unit train operation. Also, percent costs, shown in Fig. 1 were used to compare the unit train model costs with the distribution of current railroad costs. The great difference in fuel expenditures shows that unit coal trains haul significantly more than an average train and with reduced labor costs. The following data adequately express the efficiency of a unit train over a freight train.

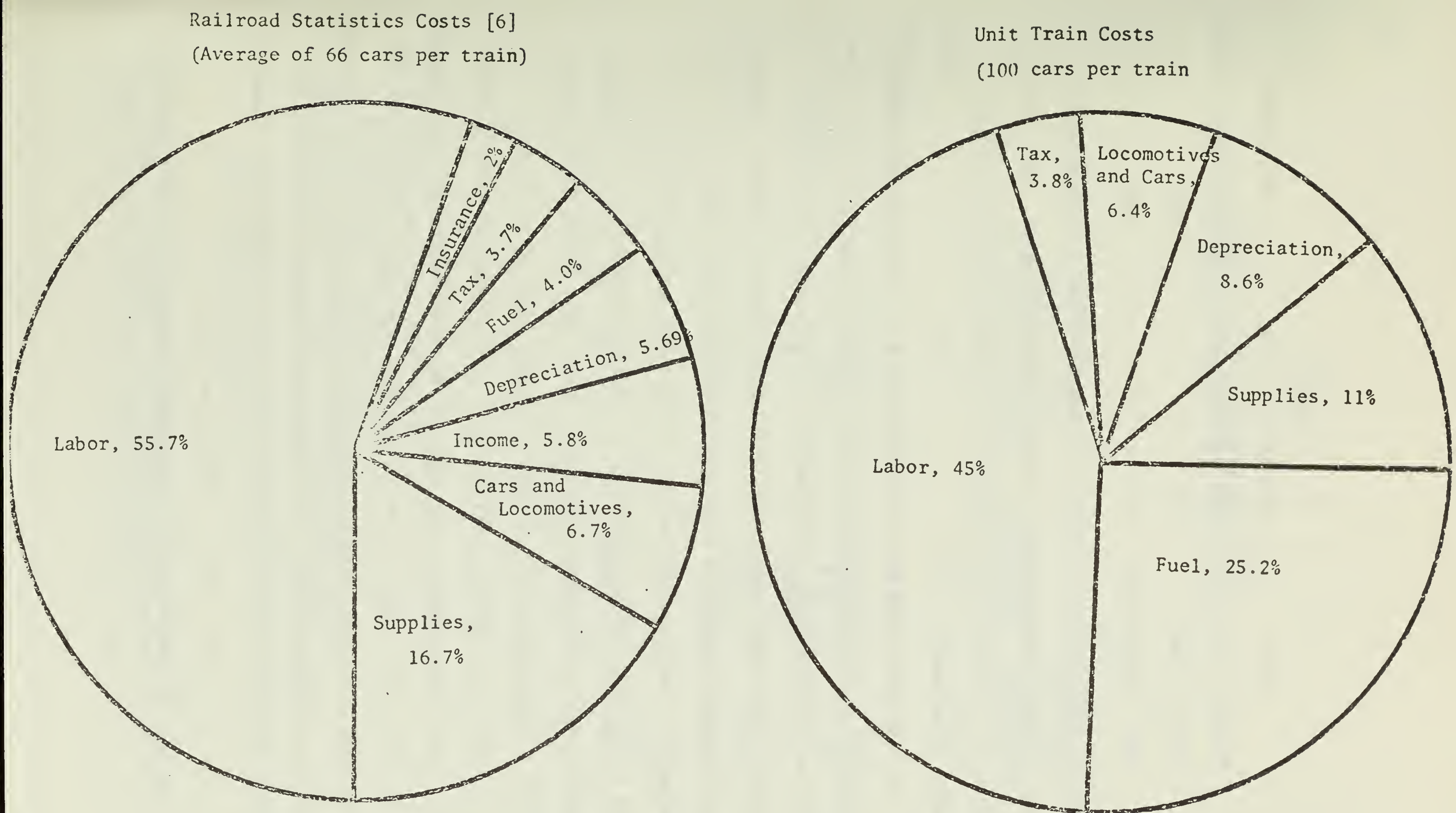

Figure 1 Percent Annual Operating Costs

Type	Freight Car [7]	Unit Train
Movement	57 miles per day	500-1,000 miles per day
Cars per train	66	100
Load, tons per car	57	100

The data illustrate why a freight car may be called a "warehouse on wheels" as they average only 57 miles per day (2.4 mph). Most of the freight car's life is spent waiting in railway yards to be switched, loaded, or unloaded.

In comparison with one particular unit train contract (see Table 1), an average rate of 0.68¢/ton-mile (0.47¢/metric ton-km) is in line with a cost of 0.52¢/ton-mile (0.36¢/metric ton-km) based on our computer modeling. The latter cost is for one million tons of coal per year using the average mileage of a Burlington-Northern unit train over a 1,050-mile route. However, when looking at the total Burlington-Northern unit train system from southern Montana and northern Wyoming, the rate of 0.68¢/ton-mile (0.47¢/metric ton-km) is over three times the calculated cost of 0.18¢/ton-mile (0.126¢/metric ton-km) based on 1,252 total train miles (2,000 km), and 16.5 million net tons per year (15 million metric tons). The tonnage used in the model of Burlington-Northern unit trains is the total from a chart of "Western Volume Bituminous Coal Rates" [6]. The mileage is from an average, weighted according to the annual tonnages. Thus, when comparing costs, it is found that railroad rates are in line with the model costs when individual routes are compared, e.g., from one mine to a particular station. This can be seen in Fig. 2.

In Fig. 2, small capacity unit trains were modeled for 0.5 to 1.5 million tons per year making trips of 100 to 600 miles to represent

Table 1

Model of Burlington-Northern
Unit Trains and Comparative Costs [6]

	Unit Train Model Costs (million dollars) 16.5×10^6 tons/yr.	Costs (percent)	1973 Railroad Costs* (percent)
Labor	14.2	45.0	55.5
Cars and Locomotives	2.0	6.4	6.7
Fuel	7.9	25.2	4.0
Depreciation	2.7	8.6	5.6
Tax	1.2	3.8	3.7
Supplies	3.5	11.0	16.7
			2.0 (insurance)
			5.8 (income)
Totals	31.5	100.0	100.0

Operating Conditions:

16,500,000 net tons per year
1,050 average one-way miles
1,252 total track miles

0.682¢/ton-mile charged (average rate), 1974
0.182¢/ton-mile computer calculated average cost

Note: (0.520¢/ton-mile computer calculated cost for 1,000,000 net tons per year)

* Economics and Finance Department of Association of American Railroads, Yearbook of Railroad Facts, Washington, D.C., 1974, p. 11.

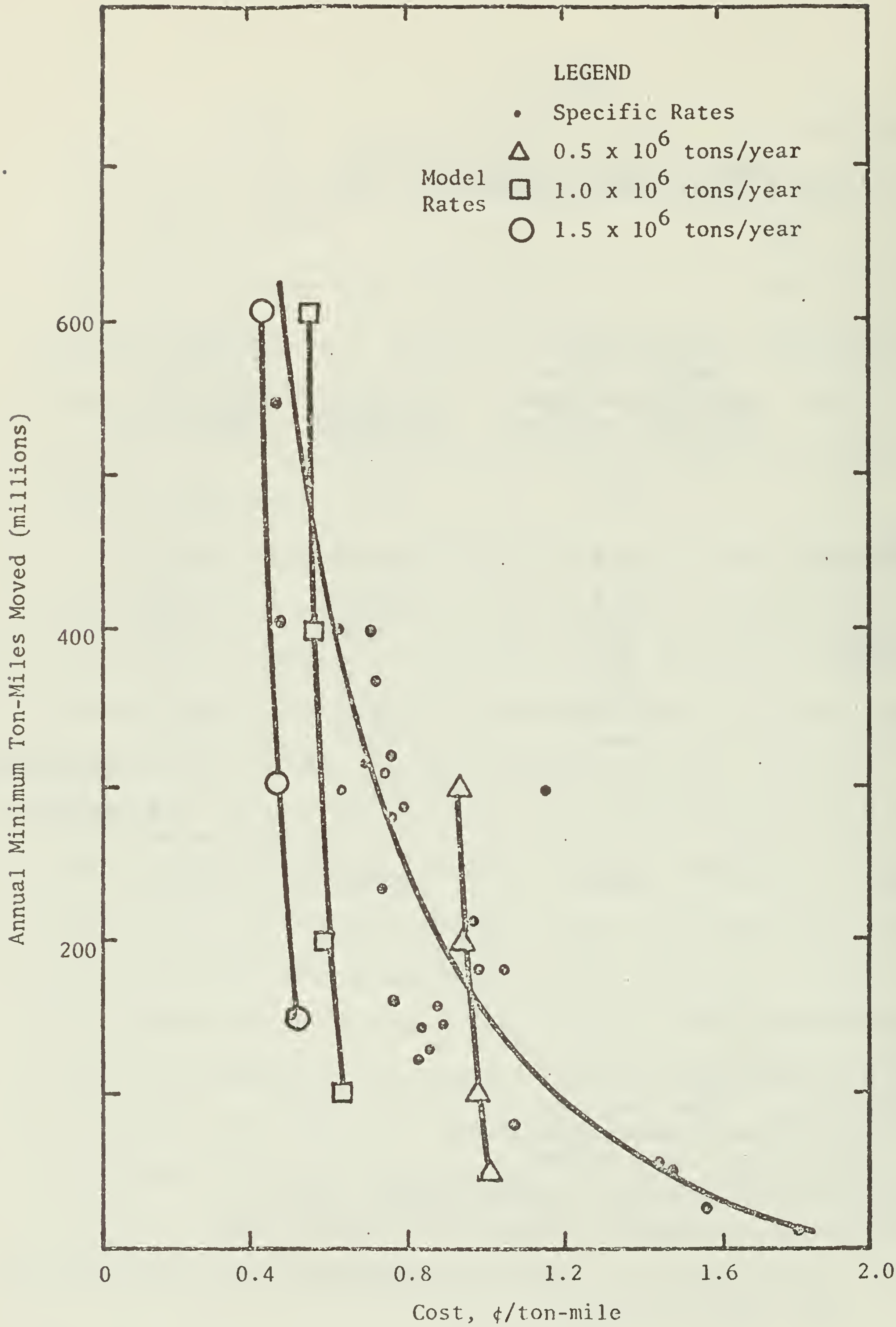

Figure 2 Representative Unit Train Rates for Eastern and Midwestern Movement [8] Compared with Model Unit Train Rates

single contracts with a mine for coal shipment. However, when comparing the model's costs with a total railroad unit train route, where several mines in an area are served by the unit trains of a particular company to several destinations in an area, the model costs are much lower because of efficient train use and lower predicted road maintenance per ton-mile. This leads to the conclusion that unit train rates do not reflect the cost when the whole system is taken into account. This may occur because often one railroad company is the only access to the mine or power plant, i.e., a monopoly rent is charged.

ANALYSIS OF THE UNIT TRAIN MODEL

The following parameters of operation and rail preparation are introduced to establish a rational basis for determining the statistical averages for cost of unit train shipment of coal and the desirability of railroad upgrading or rail building.

Speed of Trains: Fifty to 60 mph (or 80-96 kmph) means 50 mph train speed at full load and 60 mph speed for returning the empty train. This is taken as the upper range of speed of the unit train, leading to large locomotive horsepower, significantly improved road condition, but short shipping time. Thirty to 60 mph (or 48-96 kmph) means 30 mph train speed at full load and 60 mph for the empty train. This is taken as the lower economic speed of a unit train, calling for reduced locomotive horsepower but longer running time and not as stringent road condition requirements.

Rail Condition and Upgrading: New track, right-of-way, and road bed--this description means building a new railroad from scratch. New rails and ties--the existing road is upgraded to "like new" condition. Fifty to 60 mph in this case represents the best upgrading of existing rails. Track upgrading--this level of upgrading is the lowest degree of improvement that

is useful. Only 30-60 mph is considered in this case.

It is recognized that much lower speeds of operation of unit trains are in existence (each coal shipment of 4,500 tons from Perry, Illinois, to the Wood River Plant of the Illinois Power Plant in Alton, Illinois, is an overnight trip of 12 hours for a distance of 75 miles [5]); however, these are special cases and their operating parameters are not applicable to the formulation of a national energy policy. The basic parameters for comparing costs of coal shipment are dollars per ton (or dollars per metric ton) for comparing various means of shipment between two points and ¢/ton-mile (or ¢/metric ton-km) as an elementary unit for comparing different routes of shipment. The dollar per 10^9 Btu per mile (or dollar per 10^{12} Joule-km) parameter is useful when the comparison includes coal of different heating values (12,000 Btu/lb for Illinois coal and 8,000 Btu/lb for Wyoming coal).

Rather than the deluge of data made possible by the computer, a sample of the most pertinent data is presented graphically (Fig. 3, 4, and 5) so that the trends may be readily seen. Figure 3 shows the constant rate of increase in cost (¢/ton-mile) when basic construction costs increase. Costs of shipment have a slow rate of increase when construction costs multiply with minimal track upgrade or new ties and rails but the rate is steep for new roadbed. Figure 4 shows the decrease of costs with increased net tonnage over a 400-mile route. It shows that at less than 10 million net tons per year, only minimal upgrade is economic while above that, a more thorough upgrading can be sustained. Figure 5 shows the decrease in cost per ton-mile when one-way trip mileage of a route is increased. After 600 miles, there is little decrease in cost per ton-mile.

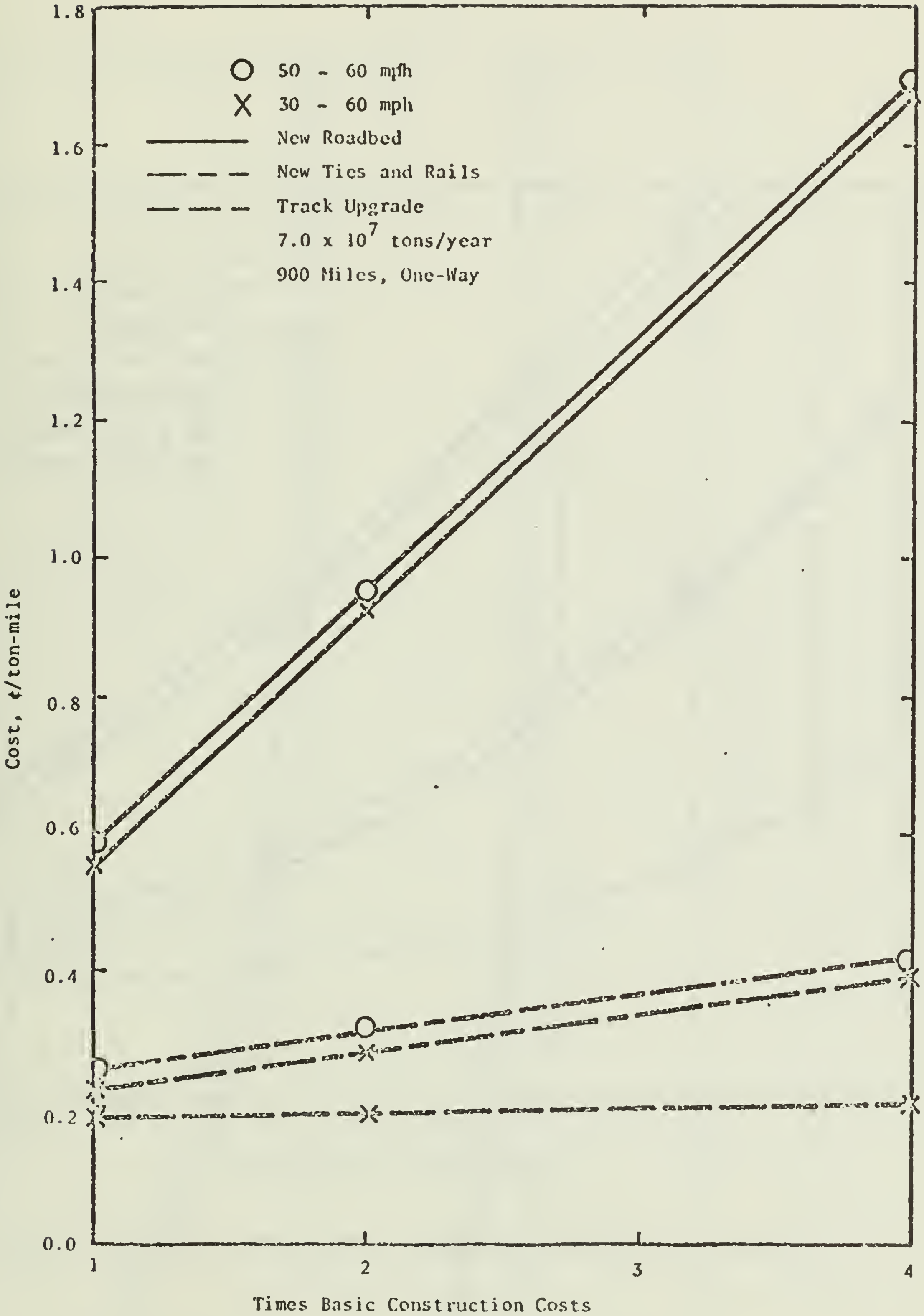

Figure 3 Increase of Rates with Multiplication of Construction Costs

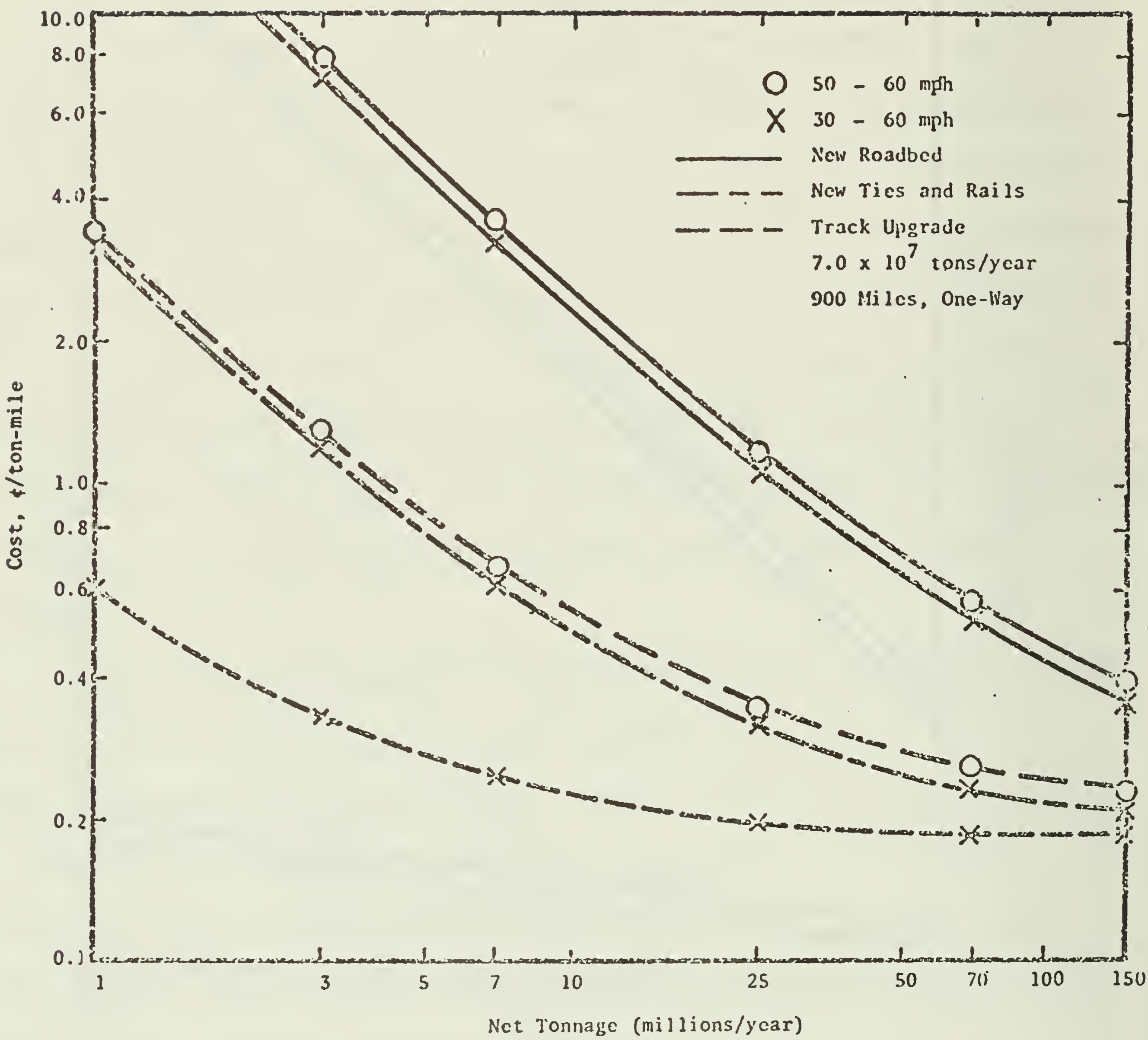

Figure 4 Decrease in Rates with Increase in Net Tonnage

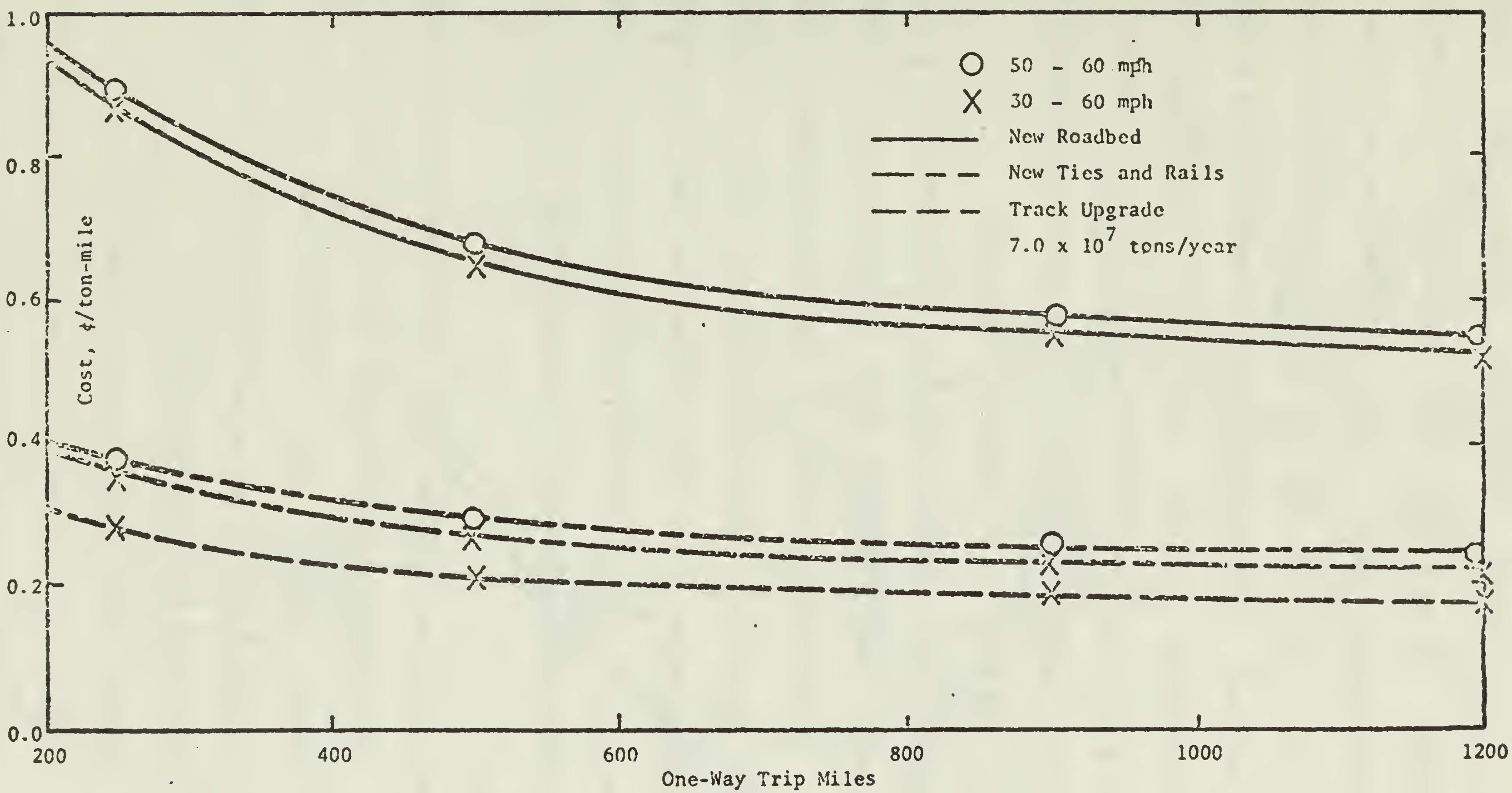

Figure 5 Decrease of Costs per Ton-Mile with Increase of One-Way Trip Mileage

Figure 6 shows the unit train routes which could be used to supply gasification plants at Pine Bluff or Fort Smith, Arkansas (6) ; Houston, Texas (8) ; or Chicago, Illinois (10) . The cost per ton for shipments via these routes are given in Table 2. Table 2 shows the unit train costs for shipping one ton of coal from the mine to the point of delivery based on 25 x 10^6 tons per year. Different degrees of upgrading and different routes of various distances are shown. The data show the economy of upgrading the existing railroad to the best form (50-60 mph). These routes are used for comparison with the proposed slurry pipeline shipment from Wyoming to Arkansas [9] and from Colorado to Texas [10].

Table 3 shows costs and resources for unit train transportation for one set of conditions given in detail. These conditions apply to the Wyoming-Chicago or Colorado-Texas route. Costs vary according to the amount of upgrading specified. Interesting features are the flexibility of degree of upgrading while operations continue and that significant employment is generated in the case of best upgrading of the existing road. The costs will be even more attractive if the operation is supported by pneumatic pipelines.

Table 4 shows costs and resources for unit trains operating via selected routes. The upgrading is to the extent of new rails and ties (best upgrading of existing rail). The costs and resources are given in detail. Low cost is achieved with a larger proportion of labor to material and energy than in the case of a slurry pipeline.

One element that must not be omitted in computing coal shipment costs is the Btu content. Because the Btu content of western coal is less than that of Illinois coal, the higher transportation cost per Btu for western coal may not justify its added value because of its low sulfur content. In

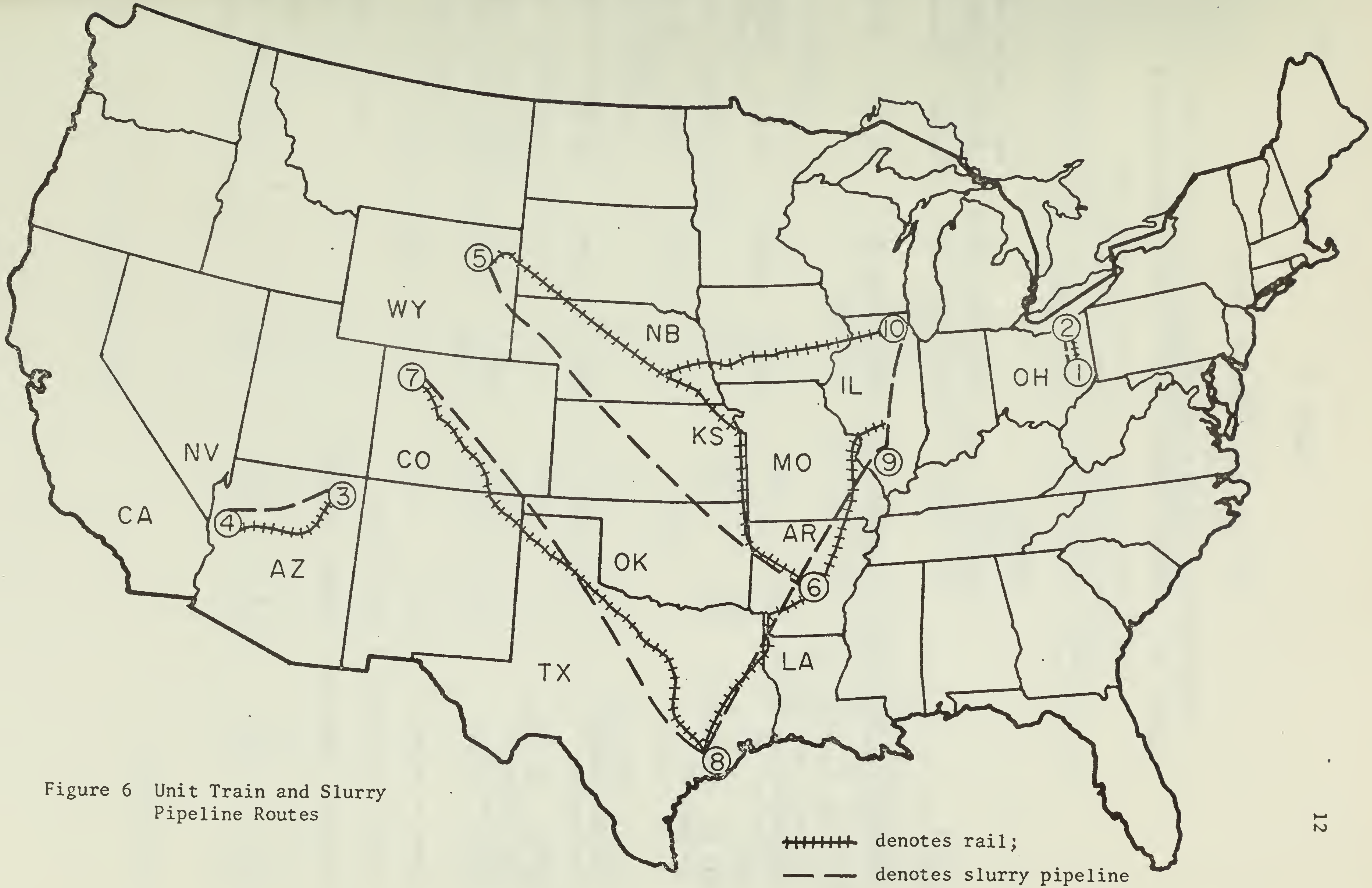

Figure 6 Unit Train and Slurry Pipeline Routes

Table 2

Unit Train Shipment Costs
(Dollars/Ton)

25×10^6 tons/year
(4×10^{14} Btu western coal or 6×10^{14} Btu Illinois coal)

Route*	Minimal Track Upgrading	New Rails and Ties		New Tracks and Right-of-Way	
	30 - 60**	30 - 60	50 - 60	30 - 60	50 - 60
(9)-(10) S. Illinois to Chicago 250 mi.	0.72	1.18	1.26	4.41	4.48
(5)-(10) Wyoming to Chicago or (7)-(8) Colorado to Texas 1,200 miles	2.41	3.80	3.92	13.50	13.62
(5)-(6) Wyoming to Arkansas 1,100 miles	2.22	3.52	3.64	12.54	12.66
(9)-(6) Illinois to Arkansas 500 miles	1.19	1.90	1.96	6.80	6.89
(9)-(8) Illinois to Texas 900 miles	1.87	2.95	3.08	10.65	10.73

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* Refer to Figure 6 for routes.

** 30 mph loaded and 60 mph unloaded.

Table 3

Costs and Resources for Unit Train Transportation
(Costs in Million Dollars)

$25x10^6$ tons/year (22.7 metric tons/year)
1,200 miles one-way (1,900 kilometers)
Wyoming to Chicago (5)-(10) or Colorado to Texas (7)-(8)
1,424 miles total double tracks (2,290 kilometers)

	Minimal Track Upgrading	New Rails and Ties		New Tracks and Right-of-Way	
	30 - 60*	30 - 60	50 - 60	30 - 60	50 - 60
CAPITAL COSTS:					
Roadbed	43	320	320	2,250	2,250
Equipment	74	74	90	74	90
Total Capital Costs	117	394	410	2,324	2,340
ANNUAL FIXED CHARGE ON DEBT:					
Average Rate Base	58.5	187.0	205.0	1,162.0	1,170.0
Debt Retirement (13.4%)	7.8	25.1	27.5	155.8	156.8
Federal Tax (28%)	2.2	7.4	7.7	43.6	43.8
Depreciation (25 yrs)	4.7	15.8	16.4	92.9	93.5
Total Annual Fixed Charge on Debt	14.7	48.3	51.6	292.3	294.2
OPERATING COSTS:					
Fuel Costs	13.7	13.7	15.2	13.7	15.2
Labor Costs	27.	27.	27.	27.	27.
Supplies Costs	6.6	6.6	6.6	6.6	6.6
Total Operating Cost	47.3	47.3	48.8	47.3	48.8

(continued)

*30 mph loaded and 60 mph unloaded.

Table 3 Continued

	Minimal Track Upgrading	New Rails and Ties		New Tracks and Right-of-Way	
	30 - 60	30 - 60	50 - 60	30 - 60	50 - 6
UNIT COSTS:					
Dollars/ton	2.48	3.82	4.02	13.58	13.72
Dollars/metric ton	(2.66)	(4.20)	(4.42)	(14.90)	(15.00
Dollars/ton-mile	0.0020	0.0032	0.0033	0.0113	0.011
Dollars/metric ton-km	(0.0014)	(0.0022)	(0.0023)	(0.0077)	(0.007
ENERGY REQUIREMENTS:					
Locomotive (hp)	300,000	300,000	530,000	300,000	530,00
Million Barrels Fuel Oil	1.60	1.60	1.80	1.60	1.80
(% energy delivered)	(2.20)	(2.20)	(2.64)	(2.20)	(2.64
EMPLOYMENT:					
Capital/Worker	.065	.220	.227	1.29	1.30
Number of Jobs* (@ $15,000/yr)	1,800	1,800	1,800	1,800	1,800

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* Figures do not include initial labor for upgrading (see Table 5) or jobs during the construction stage.

Table 4

Costs and Resources for Unit Trains
(Costs in Million Dollars)
($25x10^6$ tons/year or $22.7x10^6$ metric tons/year
New Rails and Ties
50 mph (80.5 kmph) loaded and 60 mph (96.5 kmph) unloaded

	Routes (from Figure 6)*				
	(5)-(10) (7)-(8)	(5)-(6)	(9)-(8)	(9)-(6)	(9)-(10)
...s one-way	1,200	1,100	900	500	250
...ometers one-way)	(1,930)	(1,770)	(1,450)	(804)	(402)
...s total double track	1,424	1,324	1,124	724	474
...ometers total dbl track)	(2,290)	(2,130)	(1,810)	(1,160)	(762)
...TAL COSTS:					
...adbed	320	298	253	163	107
...uipment	90	83	72	50	36
Total Capital Costs	410	381	325	213	143
...AGE FIXED ...ARGE ON DEBT:					
...erage Rate Base	205.0	190.5	162.5	106.5	71.5
...ot Retirement (0.134)	27.5	25.5	21.8	14.3	9.6
...deral Tax (28%)	7.7	7.1	6.1	4.0	2.7
...preciation (25 yrs)	16.4	15.2	13.0	8.5	5.6
Total Average Fixed Charge on Debt	51.6	47.8	40.9	26.8	17.9
...ATING COSTS:					
...el Costs	15.2	13.9	11.4	6.3	3.2
...oor Costs	27.0	23.5	19.8	12.6	8.4
...pply Costs	6.6	5.8	4.9	3.1	2.1
Total Operating Costs	48.8	42.7	36.1	22.0	13.7
...L ANNUAL COST	100.4	90.5	77.0	48.8	31.6

(continued)

Table 4 Continued

	Routes (from Figure 6)*				
	(5)-(10) (7)-(8)	(5)-(6)	(9)-(8)	(9)-(6)	(9)-(10)
UNIT COSTS:					
Dollars/ton	4.02	3.62	3.08	1.95	1.26
(Dollars/metric ton)	(4.32)	(4.01)	(3.40)	(2.16)	(1.39)
Dollars/ton-mile	0.0033	0.0033	0.0034	0.0039	0.0050
(Dollars/metric ton-km)	(0.0023)	(0.0023)	(0.0024)	(0.0027)	(0.0034)
Dollars/10^9 Btu-mile**	0.206	0.206	0.142	0.162	0.213
(Dollars/10^{12} Joule-km)	(0.122)	(0.122)	(0.084)	(0.096)	(0.126)
ENERGY REQUIREMENTS:					
Locomotive (hp)	530,000	450,000	417,000	245,000	175,000
Million Barrels Fuel	1.80	1.65	1.30	0.75	0.40
(% energy delivered)	(2.64)	(2.27)	(1.54)	(0.79)	(0.35)
Steel Required for 25 years in tons (and metric tons)					
For Locomotive	75,000	70,000	60,000	40,000	25,000
	(68,000)	(63,500)	(54,500)	(36,000)	(23,000
For Rails	550,000	510,000	435,000	280,000	185,000
	(500,000)	(460,000)	(395,000)	(254,000)	(170,000
EMPLOYMENT:					
Capital/Worker	0.227	0.243	0.246	0.254	0.260
Number of Jobs (@ $15,000/yr)	1,800	1,570	1,320	840	560
Jobs in Rail and Train Production	310	290	245	160	90
Total Jobs	2,110	1,860	1,565	1,000	650

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* (5)-(10) is Wyoming to Chicago
(7)-(8) is Colorado to Texas
(5)-(6) is Wyoming to Arkansas
(9)-(8) is Illinois to Texas
(9)-(6) is Illinois to Arkansas
(9)-(10) is Illinois to Chicago

** 12,000 Btu Illinois coal and 8,000 Btu western coal.

fact, some of the western coal does not meet pollution control standards.

At the present time, there are unquantifiable costs for strikes and insurance. These may need to be added. Also, there may be added costs for road overpasses and crossings because at 70 x 10^6 tons of coal per year, a train would pass by a given point every 40 minutes. These overpasses or underpasses, which cost from $400,000 up, are shared by the railroad and highway with the former usually paying 10 to 20 percent [11].

RESOURCES USED BY UNIT TRAINS

There is an old saying, "There is no free lunch," which applies to the unit train. The resources used by unit trains are needed for, and must be compared with, other modes of transportation.

The resources required for a 1,200-mile (1,920 km) route from Wyoming to Arkansas, hauling 25 million tons (21.8 million metric tons) of coal per year, is given in Tables 3 and 4 along with the resources required for other potential routes.

Rail is one of the most efficient sources of transportation. Column 1, Table 4 shows about 1.6 million barrels of diesel fuel per year at a 30 mph (48 kmph) hauling speed, or up to 1.8 million barrels at 50 mph (80 kmph), unless methanol or electricity is used for power. This may be justified considering that the coal hauled produces 4 to 6 x 10^{14} Btu (3.8 to 5.7 x 10^{14} kilojoules) while the fuel oil could produce 1 x 10^{13} Btu (0.95 x 10^{13} kilojoules) representing 2 percent of the energy. In the long run, however, diesel locomotives will probably be replaced by large horsepower gas turbine locomotives fueled by methanol produced from coal gasification products.

The use of human resources may be more or less favorable than capital investment depending on the unemployment situation and interest rates.

Considering track upgrade only, the preceeding 25 million tons of coal per year shipping rate would pay out about 45 percent of the $60 million annual costs to direct labor. This would mean a $27 million payroll for 1,800 jobs at $15,000 a year. If there was a shortage of workers, it should be possible to run the trains by remote control. Besides these direct labor costs, there are indirect labor costs for manufacturing locomotives, cars, rails, and ties.

Presently, there is a shortage of hopper cars [4]. In overcoming this problem, the present unemployment rate could be lessened. Two thousand sixty additional 103.5-ton (93-metric ton) capacity cars would be needed for the 25 million tons of coal per year unit train system as well as ninety, 3,000 hp diesel locomotives (or thirty, 10,000 hp gas turbine locomotives). This would mean jobs and would require about 75,000 tons (68,000 metric tons) of steel. The double track would need about 550,000 tons (500,000 metric tons) of steel to last 25 years. This can be compared to the 1973 U.S. production of 150 million tons (137 million metric tons) [12] of raw steel. This steel production would furnish about 160 jobs. The capital required for a unit train system of this size for 30 mph (48 km) hauling, including only track upgrade, is $116.8 million and, if starting with new ties and rails, is $394.4 million.

FUTURE OF COAL TRANSPORT BY RAIL

Looking toward the future, even an inflation rate of only 7 percent results in a cost doubling every ten years. However, what is important is the relative effect of inflation on competing transport modes. With long overdue improvements, the railroads may be able to compete because of their high energy use efficiency. If diesel fuel becomes scarce or too high priced, future locomotives may be powered by gas turbines using

methanol from gasification or electricity from coal burning or nuclear power stations.

Because of the heavy loads and fast speeds of a unit train, continuous rails and concrete ties [13] and a continuous concrete slab roadbed [14] may be used to decrease maintenance. Increased traffic calls for improved signaling and switching systems and more overpasses.

The operation of unit trains suffers from the lack of a back haul to the mining area. It is here that the biggest opportunity for cost reduction exists. Even a marginal system, such as sewage for fertilizer and ash from coal for land reclamation, could make the return trip productive.

Rail operation is further faciliated by the use of pneumatic pipelines. While high pressure, long distance pneumatic systems remain to be developed [1], short distance pneumatic pipelines of one to 20 miles (32 km) can be furnished with current technology (see APPENDIX). These lines, carrying up to 2,400 tons (2,200 metric tons) per day of 2 in. by 0 in. coal can be used in place of abandoned rail lines in gathering to, and distributing from, unit train terminals. Future development will furnish pneumatic pipelines of the level of 10,000 tons per day over hundreds of miles [1].

Rail transportation's biggest hurdle is overcoming its worsening public image. Without a better image, increased cost effectiveness and new ideas for increasing revenue, there may be no private investment for growth. Some badly managed systems would disappear without government subsidy. They have not already done so because they have not been permitted to become bankrupt [15]. Given the level of subsidy and government aid, one solution is for the government to own and maintain alternative unprofitable tracks. Railroads would become similar to highways

and rivers. Continued subsidy or federal ownership would allow more competition in transport from the mine to the consumer. Unprofitable tracks need to be studied to see if their service could be carried out profitably by other modes of transportation. Subsidies or federal ownership of the tracks should be the last resort and should be compared with those for highway, river, and air transport so that intermodal competition can be maintained.

PART II: SLURRY PIPELINES

Two slurry pipelines have been built and tested. The first was the 108-mile (173 km) long, 10 in. (0.254 m) pipeline completed in 1957 for shipping coal from the Consolidated Coal Company mine in Cadiz, Ohio, to the East Lake Power Plant of the Cleveland Electric Illuminating Company [16]. Its cost of operation became unfavorable subsequent to the downward adjustment of competing unit train rates. Recently, it has been used for removing garbage from Cleveland. The second pipeline is the 273 mile (436 km) long, 18 in. (0.457 m) pipeline connecting the Black Mesa mines to the Four Corners Power Plant. It was built because of its economy compared to the cost of building 150 miles (240 km) of new railroad to connect with the Santa Fe railroad at both ends [17]. Much has been learned from its design, operation, and costs. The Black Mesa Pipeline provided a basis for projecting the needs and costs of new routes for coal shipment via slurry pipelines. These pipelines are marked 1 - 2 and 3 - 4 on the map shown in Fig. 6.

The most undesirable feature of a slurry pipeline is the water requirement. The pipeline needs large quantities of water for product flow. In the western mining area, water is in relatively short supply. At the destination, separation yields a residual "ink" which cannot be dumped into rivers. At the Four Corners Plant, water must be evaporated to prevent pollution. Piping the waste water back to the starting point for reuse in the slurry would require a 40 percent higher owning and operating cost of the shipped coal because the waste water must be pumped upgrade to the mining area.

The second problem is the need to dump the paste-like slurry from all previous sections in the event of a pipeline break or total power failure at a pumping station. This may amount to as much as a million tons of coal [21]. There is no immediate solution to these two problems. Potential environmental impacts could prevent the utilization of slurry pipelines.

PROPOSED SYSTEMS UNDER CONSIDERATION

Given a possible tripling of coal utilization [18], particular routes may be expected to handle even larger increases. Prominent are those from Gillette, Wyoming, to White Bluff, Arkansas, and from Craig, Colorado, to Houston, Texas [19]. Both are based on shipping low sulfur western coal for gasification at the destination. Both slurry pipeline and railroads [3] have been considered. The assumption has been that only low sulfur, low Btu coal (less than one percent by weight and about 8,000 Btu/lb) will be used.

An alternate source of coal that will become useful with the anticipated development of methods for using high sulfur coal for gasification is high Btu (12,000 Btu/lb) sulfur (up to 5 percent) Illinois coal. Shipments would include those from southern Illinois to Chicago or to Arkansas and Texas via unit trains or slurry pipeline. High Btu coal gasification at convenient points followed by piplining to the consumption points is another alternative.

COSTS

Future cost trends and the economic and environmental impact of slurry pipelines can be seen in the recent plan of the Wyoming to Arkansas line [20] as well as from reports on the Black Mesa pipeline [21,22]. Several economic analyses of slurry pipelines have been presented [2,23].

The difference in cost escalation rates of 4 percent for the pipeline and 7 percent for rail [12] are suggested. The high costs of preparation and separation were especially noted by Hughes [24]. Data from these sources were used in the computations leading to Table 5 which summarizes the cost and physical magnitudes of several of the pipelines identified in Fig. 6. Physical quantities of particular interest are water requirements (acre-ft/yr), total installed horsepower, and coal hold-up. The costs can then be compared to unit train costs of operation to the same destination. Slurry pipelines cost one-half as much as a new railroad but are double the cost of the best upgrading of existing railroad. The large coal hold-up in a slurry pipeline (855,000 tons of coal in the proposed Wyoming to Arkansas line) poses an unsolvable problem in case of power outage.

The topology of the Black Mesa pipeline has been presented in several references [21,22]. Figures 7a and 7b show the relatively easy downhill trend for the Wyoming to Arkansas pipeline and the difficult terrain of the Colorado to Texas pipeline. Figure 8 gives the general cost distribution for a slurry pipeline.

Pipeline costs are given in Table 5. Note that variations are around 1¢/ton-mile because of possible state taxes. Also included in Table 5 are the costs of unit train shipments for those routes shown in Fig. 6, assuming the use of available railroads. The method of arriving at the rail figures for 30 mph (loaded)-60 mph (empty) and 50 mph (loaded)-60 mph (empty) is given in previous studies [25] for various qualities of railroads including new road bed and rail, new rails and ties, or track upgrading. This comparison shows that, except for building an entirely new railroad, slurry pipelines cannot compete in cost of shipment even with the most complete upgrading of the railroad. The rail advantage is even

Table 5

Costs of Slurry Pipeline in Comparison to Rail
(Costs in Million Dollars)

	Ohio (1)-(2)	Black Mesa (3)-(4)	Wyoming - Arkansas (5)-(6)	Colorado - Texas* (7)-(8)	Illinois - Chicago (9)-(10) Illinois - Arkansas (9)-(6)	Illinois - Texas* (9)-(
CAPITAL COSTS:						
A. Preparation equipment and wells		50	90		90	90
Tons/year	$1.5x10^6$	$5x10^6$	$25x10^6$	$25x10^6$	$25x10^6$	$25x10^6$
B. Piping and installation	10"D(108mi)	18"D(273mi)	38"D(1040mi)	38"D(1200mi)	38"D(300mi)	38"D(700mi)
Electrical transmission (1 pumping station/90 miles)		60	894	1,133	261	609
C. Separation plant and water disposal		40	50		50	50
TOTAL CAPITAL COSTS		150	1,034	1,133	401	749
ANNUAL COSTS:						
A. Annual fixed charge on debt. Average rate base.		75	517		200.5	374.5
Debt Retirement						
Rate base (13.4%)		10.1	69.3		26.9	50.2
Federal Tax (28%)		2.5	16.9		6.6	12.3
Depreciation (25 years)		6.0	41.4		10.0	30.0
(State Tax, 2% on Inv.)		(2.0)	(20.7)		(8.0)	(15.0)
Total Debt Retirement		21.6	148.3		51.5	107.5
B. Operating Labor Direct (no. of men)		1.6 (84)	4.6 (245)		2.9 (152)	3.6
Administrative		0.8	2.3		1.4	1.8
C. Material and maintenance supplies		1.0	6.0		4.0	5.0
Total of B and C		3.4	12.9		8.3	10.4
D. Power (installed horsepower)		1 (21,000)	15.9 (190,000)	(210,000)	7.4 (55,000)	12
E. Water (acre/foot/year)		0.5 (3,000)	3.5 (15,000)	(15,000)	3.5 (15,000)	3.5
TOTAL ANNUAL COSTS		26.5	180.6		70.7	133.4
(Total annual costs w/o state tax)		(24.5)	(159.9)		(62.7)	(118.4)
F.						
a. $/ton including state tax		5.30	7.22	9.11	2.83	5.34
b. $/ton excluding state tax		4.69	6.40	8.12	2.51	4.70
c. $\$/10^9$ Btu-mile including state tax		1.21	0.43	0.48	0.39	0.32
d. $\$/10^9$ Btu-mile excluding state tax		1.07	0.39	0.43	0.35	0.28
e. ¢/ton-mile including state tax		1.94	0.69	0.76	0.95	0.76
f. ¢/ton-mile excluding state tax		1.72	0.62	0.68	0.84	0.68
Hold-up in Pipe in tons at 3.5 mph		46,000	855,000	1,000,900	250,000	580,000
Comparison to Rail in cents/ton-mile						
New road, 50-60/30-60 mph			1.15/1.12	1.14/1.13	1.78/1.78	1.19/1.17
New rail, 50-60/30-60 mph			0.33/0.31	0.33/0.32	0.50/0.49	0.34/0.32
Track upgrading, 30-60 mph			0.19	0.20	0.30	0.20
Trains on the road, 50-60/30-60 mph			13/16	13/16	3/5	10/14
Total locomotive horsepower:						
50-60 mph			450,000	530,000	175,000	420,000
30-60 mph			250,000	300,000	90,000	240,000
Cost $\$/10^9$ Btu-mile, new rail 50-60 mph			0.206	0.206	0.162	0.142

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* Difficult Terrain

Table 5
METRIC

Costs of Slurry Pipeline in Comparison to Rail
(Costs in Million Dollars)

COSTS:	Ohio (1)-(2)	Black Mesa (3)-(4)	Wyoming - Arkansas (5)-(6)	Colorado Texas* (7)-(8)	Illinois - Chicago (9)-(10) Illinois - Arkansas (9)-(6)	Illinois - Texas* (9)-(8)
aration equipment and wells		50	90		90	90
ic Tons/year	$1.35x10^6$	$4.5x10^6$	$22.6x10^6$		$22.6x10^6$	$22.6x10^6$
ng and installation	.253mD(173km)	.457mD(436km)	.965mD(1670km)	.965mD(1930km)	.965mD(480km)	.965mD(1200km)
trical transmission umping station/145 kilometers)		60	894	1,133	261	609
ration plant and water disposal		40	50		50	50
L CAPITAL COSTS		150	1,034	1,133	401	749
OSTS:						
al fixed charge on debt. age rate base.		75	517		200.5	374.5
Retirement:						
te base (13.4%)		10.1	69.3		26.9	50.2
deral Tax (28%)		2.5	16.9		6.6	12.3
preciation (25 years)		6.0	41.4		10.0	30.0
tate Tax, 2% on Inv.)		(2.0)	(20.7)		(8.0)	(15.0)
Total Debt Retirement		21.6	148.3		51.5	107.5
ating Labor Direct (no. of men)		1.6 (84)	4.6 (245)		2.9 (152)	3.6 (191)
nistrative		0.8	2.3		1.4	1.8
rial and maintenance supplies		1.0	6.0		4.0	5.0
Total of B and C		3.4	12.9		8.3	10.4
r (kilowatt)		1 (16,000)	15.9 (140,000)	(157,000)	7.4 (41,000)	12 (95,000)
r (cubic meters/yr)		0.5 ($3.7x10^6$)	3.5 ($18.5x10^6$)	($18.5x10^6$)	3.5 ($18.5x10^6$)	3.5 ($18.5x10^6$)
. ANNUAL COSTS		26.5	180.6		70.7	133.4
l annual costs w/o state tax)		(24.5)	(159.9)		(62.7)	(118.4)
/metric ton incl. state tax		5.85	7.95	10.10	3.12	5.88
/metric ton excl. state tax		5.17	7.05	8.95	2.77	5.20
$/10^{12}$ Joule-kilometer incl. state tax		0.80	0.28	0.32	0.26	0.21
$/10^{12}$ Joule-kilometer excl. state tax		0.71	0.20	0.28	0.23	0.19
/metric ton-kilometer incl. state tax		1.34	0.48	0.52	0.65	0.52
/metric ton-kilometer excl. state tax		1.19	0.43	0.47	0.58	0.47
n Pipe in metric tons at 5.60 kmph		42,000	775,000	910,000	230,000	525,000
n to Rail in cents/metric ton-km						
oad, 80-97/48-97 kmph			0.79/0.77	0.79/0.78	1.23/1.23	0.82/0.81
ail, 80-97/48-97 kmph			0.23/0.21	0.23/0.22	0.34/0.34	0.24/0.22
upgrading, 48-97 kmph			0.13	0.14	0.21	0.14
s on the road, 80-97/48-97 kmph			13/16	13/16	3/5	10/14
locomotive power, kilowatt:						
0-97 kmph			336,000	395,000	130,000	313,000
8-97 kmph			186,000	224,000	67,000	179,000
^{12} Joule-kilometer, new rail 80-97 kmph			0.136	0.121	0.107	0.094

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lt Terrain

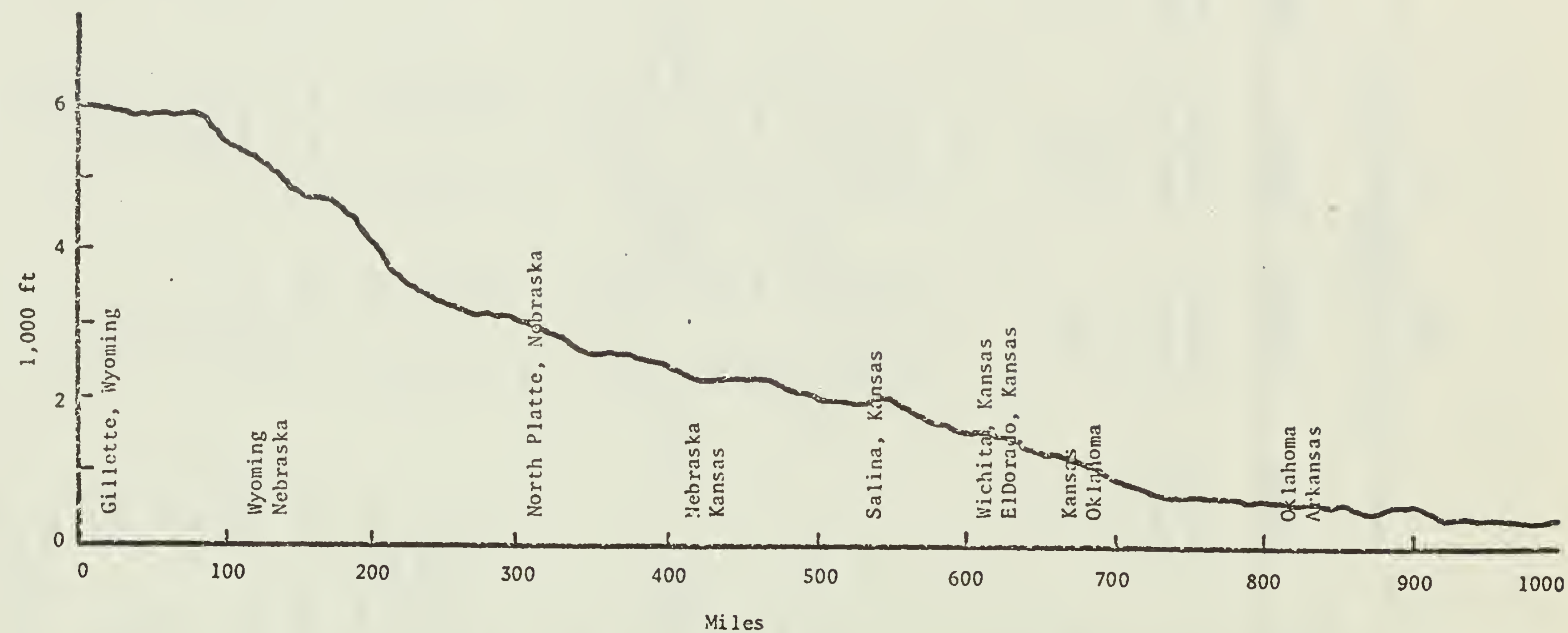


Figure 7a Elevation of Wyoming to Arkansas

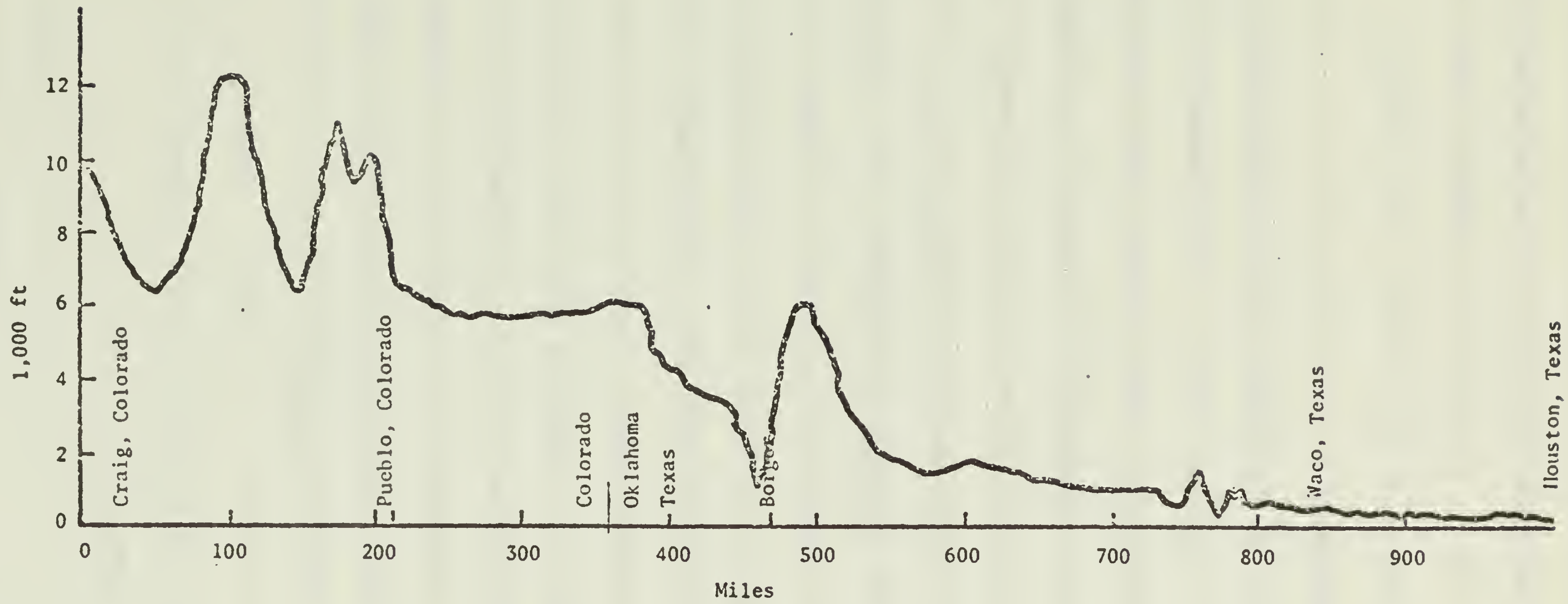


Figure 7b Elevation of Colorado to Texas

Slurry pipelines and unit trains are directly competitive alternatives

greater if one considers that the railroad may carry other, non-coal shipments while the slurry pipeline is a one-material shipper. The use of complementary pneumatic pipelines in conjunction with rail would further improve the economics of the railroad (see APPENDIX).

ENVIRONMENTAL IMPACT

The design of the Black Mesa pipeline specifies dumping the coal slurry in case of power failure. The problem for a 273-mile (436 km) line with three pumping stations and a 46,00 ton (42,000 metric ton) coal hold-up is minor compared to a 1,040-mile (1,670 km) line with 10-12 pumping stations and a hold-up of 855,000 tons (775,000 metric tons).

In case of power failure or pumping outage at a station, the slurry cannot be stopped lest deposition and plugging occur. The procedure entails introducing water into the pumps at the upstream station and dumping the slurry ahead of the nonoperating station. The latter might require an auxiliary water pump and water supply at the next operating station as suction alone might not be sufficient to pull the slurry through. The case of a line break can be similarly handled at upstream points; however, there is no provision made such that the downstream pump can pull the slurry through the downstream section of the break. Hence, the design excludes line breakage. Baccheti [27] has indicated that no outages have occurred in the Black Mesa pipeline. A controlled shut-down is no problem: Stopping the coal supply at the starting point and introducing water instead will clear the line in 78 hours by replacing slurry with water.

In a 1,040-mile (1,670 km) pipeline, it will take 12 days, 9 hours to clear the line in a controlled shutdown. While line breakage might be excluded by extra-heavy piping, there is no guarantee that power outage

will not occur at one of the 10-12 pumping stations. Provision for dumping at a station calls for a large water supply and auxiliary water pumping capacity at that station.

ECONOMIC IMPACT

While the material and energy costs related to upgrading a railroad and the number of locomotives and cars required to carry vastly increased coal shipments is high, these are not the sole criteria. For example, the locomotive horsepower required for a unit train shipment is of the same order of magnitude as the installed horsepower for a slurry pipeline of similar length. The manufacture of locomotives and cars for a 16-train unit train operation includes 64,000 tons (58,000 metric tons) of steel. This may be compared to a slurry pipeline (Wyoming to Arkansas) using 1.1 million tons (1.0 million metric tons) of steel for the pipeline alone, or almost twice as much as that required for the rails of the 1,100 miles (1,770 km) of double track railroad. Therefore, the material requirements for upgrading the railroad are less than for a new pipeline; the rolling stock is actually a small factor in the material investment. The employment generated by the rail upgrading can be a big factor in the recovery from the current recession. Employment for rail upgrading can be long term, steady employment requiring a variety of skilled labor; employment generated by a pipeline is short term and not as variable.

COMPARISON TO RAILS

A 7 percent annual escalation of costs for railroads and a 4 percent annual escalation for slurry pipelines has been predicted [23]. However, for the present comparison of 1975 installation costs, a uniform 7 percent annual escalation of costs is assumed.

In terms of engineering and operation, a slurry pipeline must be

designed for an optimum throughput and must be kept filled. The flow rate must be kept near the optimum for economic operation. In order to double the capacity of a given slurry line, four times the pumping power and fuel is needed. That is why slurry lines are designed for an optimum throughput causing a lack of operating flexibility.

The cost of multiple pipelines to improve reliability of operation is exhorbitant. The capacity of two 27-inch pipelines, equaling that of the 38-inch pipeline for 25 million tons per year of coal, would cost 1.6 times* as much to build. In addition, because of higher friction in smaller pipes, they would require 1.45 times the pumping power and fuel for the larger diameter line [30].

Rails are far more flexible during upgrading, and development and growth can be programmed. If there is an accident, there is relatively little damage. Also, with double track, because of switching systems, parts of one track can be closed for upgrading or repair without impeding traffic.

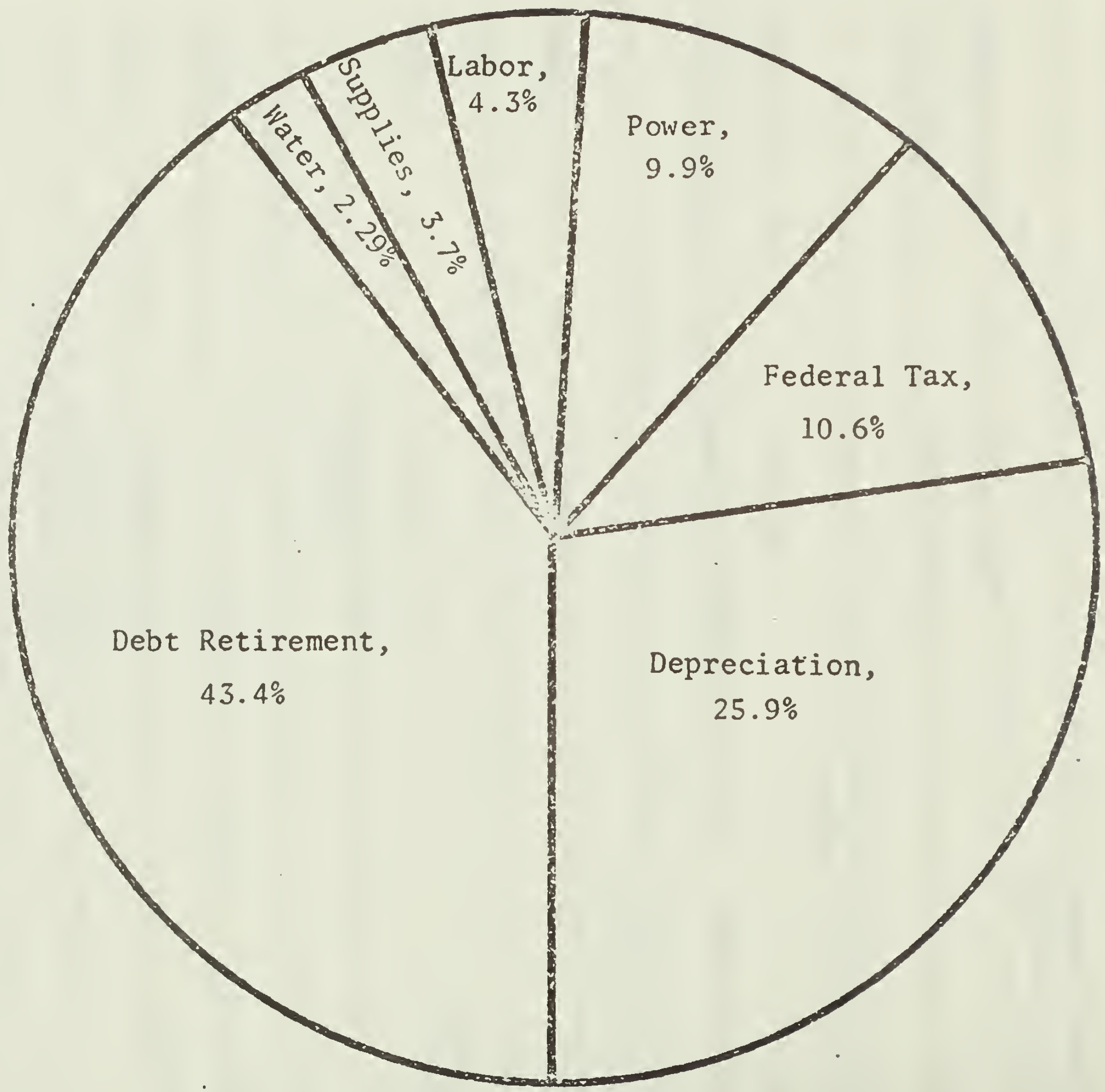
A slurry pipeline is more capital intensive than unit train operations. The depreciation of a unit train is 8.6 percent of its cost compared to 27.4 for slurry for the Wyoming to Arkansas shipment. Table 6 illustrates the labor employment generated by the Wyoming to Arkansas coal transport system. For the same route, 5 - 6, Table 4 gives 26.9 percent of the owning and operating cost of unit train operation for labor compared to 4.3 percent for slurry pipeline as given by Table 5 and as shown in Fig. 8. The initial labor (from Table 6) totals 9,000 man-years for rail compared to 7,500 man-years for slurry. The continuing labor is likewise higher for rail at 1,800 compared to 245 for slurry.

*According to the U.S. Army Corp of Engineers cost predictions:
Cost of 27-inch piping = (Cost of 38-inch piping) x $[(27/38)^{0.65}]$.

Table 6

Comparison of Employment Generated
(25 Million Tons/Year, Wyoming to Arkansas)

	Rail (Upgrading to 50 - 60 mph)	Slurry Pipeline (New)
Initial Material and Energy Total Steel:		
Tons	500,000	1.1 million
Installed hp.	450,000	190,000
Initial Construction Labor:		
Man-Years	6,000	4,500
Installation Time	(Over 3 years)	(Over 2 years)
Equipment Acquisition:		
Man-Years	3,000	3,000
Continuing Labor Replacement	150 (Rail)	300
	150 (Rolling Stock)	
Operation	500	180
Maintenance	400 (Rail)	65
	250 (Cars)	
	350 (Locomotives)	
Total, continuing labor	1,800	545



Slurry Pipeline Percent Costs

Figure 8 Comparative Percent Owning and Operating Costs

If interest rates drop low enough, slurry pipelines could become economic and, with technological improvements, less risky but, until then, an upgraded rail system is both more economical and labor intensive.

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APPENDIX

PNEUMATIC PIPELINE

Based on current practice, a pneumatic pipeline appears most competitive with trucks and belt conveyors for gathering to, and distribution from, a rail terminal. Details are summarized in Table 7, showing the design variables. Pressure feed is limited to 20 psig such that high pressure feed bins and switching are not needed while the vacuum suction is limited to -10 psi vacuum as an economic limit. Table 7 shows various push-pull options. Table 7 shows distances of up to 4.5 miles (7.2 km); however, a longer distance line can be designed. For instance, one way to cover a distance of 18 miles (28.9 km) is to repeat by using four modules of 4.5 miles (7.2 km) each. Since the gravity effect is not a big factor in the prssure drop in a pneumatic system, the latter can cover the steepest terrain using the most direct route. Since very little ground preparation is needed for installing a pneumatic system, it is almost portable if relocation is needed.

The cost of shipment via these pneumatic pipelines of low capacity ranges from 3¢/ton-mile at between 400 tons per day and 2,000 tons per day to from 1 to 2¢/ton-mile for shipment above 2,000 tons per day. Because this system is more recent than the others, its details are delineated below.

PNEUMATIC COAL TRANSPORT SYSTEM [1,28]

A technical and economic evaluation of pneumatic coal pipelining has been made in an experimental installation as shown in Fig. 9. Test parameters include the coal rates and sizes that can be efficiently conveyed pneumatically, pipe sizes, air volume and compression power requirements, and pipe erosion. Technical feasibility depends mostly on

Table 7 Design Parameters--Current Pneumatic Pipelines for Short Distances, 2 in. x 0 in. (5.08 cm by 0 cm) Coal, Unpressurized Coal Feed

Capacity		
Tons/yr;	100,00	500,000
Tons/hr	20	100
Pipe Diameter, in. (cm)	10 (25.4)	18
Air Flow, scfm	2,500	12,000
1,000 ft (304.8 m) Transfer		
Pressure Drop, psi	2.8	1.4
Inlet Pressure	Atmospheric	Atmospheric
Discharge Suction, psi vac	-2.8	-1.4
Blower hp at Discharge	50	125
Installed Cost	$200,000	$600,000
1 mile (1.6 km) Transfer		
Pressure Drop, psi	14.7	7.3
Inlet Pressure, psig	15*	Atmospheric
Blower hp at Inlet	250	---
Discharge Suction, psi vac	Atmospheric	-7.3
Blower hp at Discharge	0	650
hp/(ton/hr)	12.5	6.5
Installed Cost	$216,000	$648,000
1.5 Mile (2.4 km) Transfer		
Pressure Drop, psi	22	
Inlet Pressure, psig	15*	
Blower hp at Inlet	250	
Discharge Suction, psi vac	-7	
Blower hp at Discharge	125	
Installed Cost	$226,000	
2 Mile (3.2 km) Transfer		
Pressure Drop, psi		14.7
Inlet Pressure, psig		15*
Blower hp at Inlet		1,250
Discharge Suction, psi vac		Atmospheric
Installed Cost		$696,000
3 Mile (4.8 km) Transfer		
Pressure Drop, psi		22
Inlet Pressure, psig		15*
Blower hp at Inlet		1,250
Discharge Suction, psi vac		-7
Blower hp at Discharge		600
Installed Cost		$744,000
4.5 Mile (7.2 km) Transfer		
Pressure drop, psi		30
Inlet Pressure, psig		20**
Blower hp at Inlet		1,650
Discharge Suction, psi vac		-10***
Blower hp at Discharge		800
Installed Cost		$872,000

*With rotary feeder (A. S. H. Fluid Transport Division, Envirotech Corporation King of Prussia, PA 19406).

**Limit of rotary-valve feeder.

***Limit of [illegible]

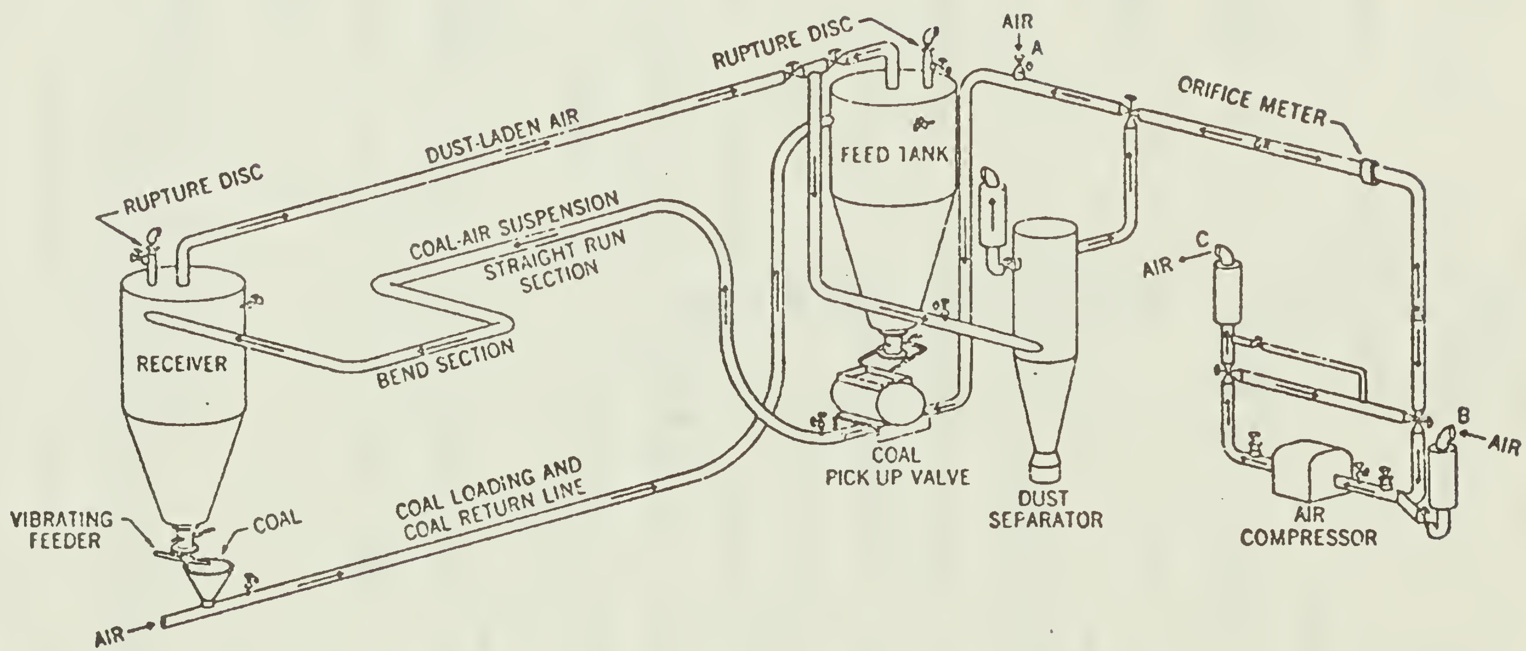

Figure 9 Sketch of Experimental Pneumatic Coal Transport Plant showing Typical Components

whether a pneumatic system can be successfully operated and whether it can meet or exceed the haulage capabilities of existing systems. Economic feasibility depends largely on the capital and operating costs of air compression equipment. Haulage capabilities and air requirements thus appear to be the major factors needing study. These, in turn, vary in accordance with characteristics of the pneumatic system (horizontal or vertical, vacuum or pressure); the diameter, length, and configuration of the pipe; and the size, size distribution, moisture content, and ash (slate and shale) content of the coal. Data are desired for as wide a range possible of coal characteristics, pipe specifications, and pneumatic techniques. Also, desirable information on the erosion of pipe and bends, coal degradation, and mechanical techniques.

Figure 9 is a sketch of the experimental pneumatic coal transport pilot plant which incorporates components which might be used in actual installations, although not simultaneously. Four pipelines of different diameters consisting of straight horizontal runs and bends lead from a 7-ton feed tank to a receiver. The four pipelines are 2, 4, 6 and 8 inches in diameter and are made of mild steel. Straight runs of 200 feet in length are followed by shorter runs containing 8, 6, and 4 foot bends in succession.

Thd 2,500 cfm compressor in the system permits operation at vacuum to 20 inches mercury and pressures to 20 psig. During vacuum operation, air enters the system at point A, picks up coal at the rotary valve (Fig. 10), and the coal-air suspension is pulled through the test piping. The coal is deposited in the receiver. Dusty air from the receiver is pulled into the dust-separator for cleanup, and the clean air proceeds through the compressor and is discharged into the atmosphere.

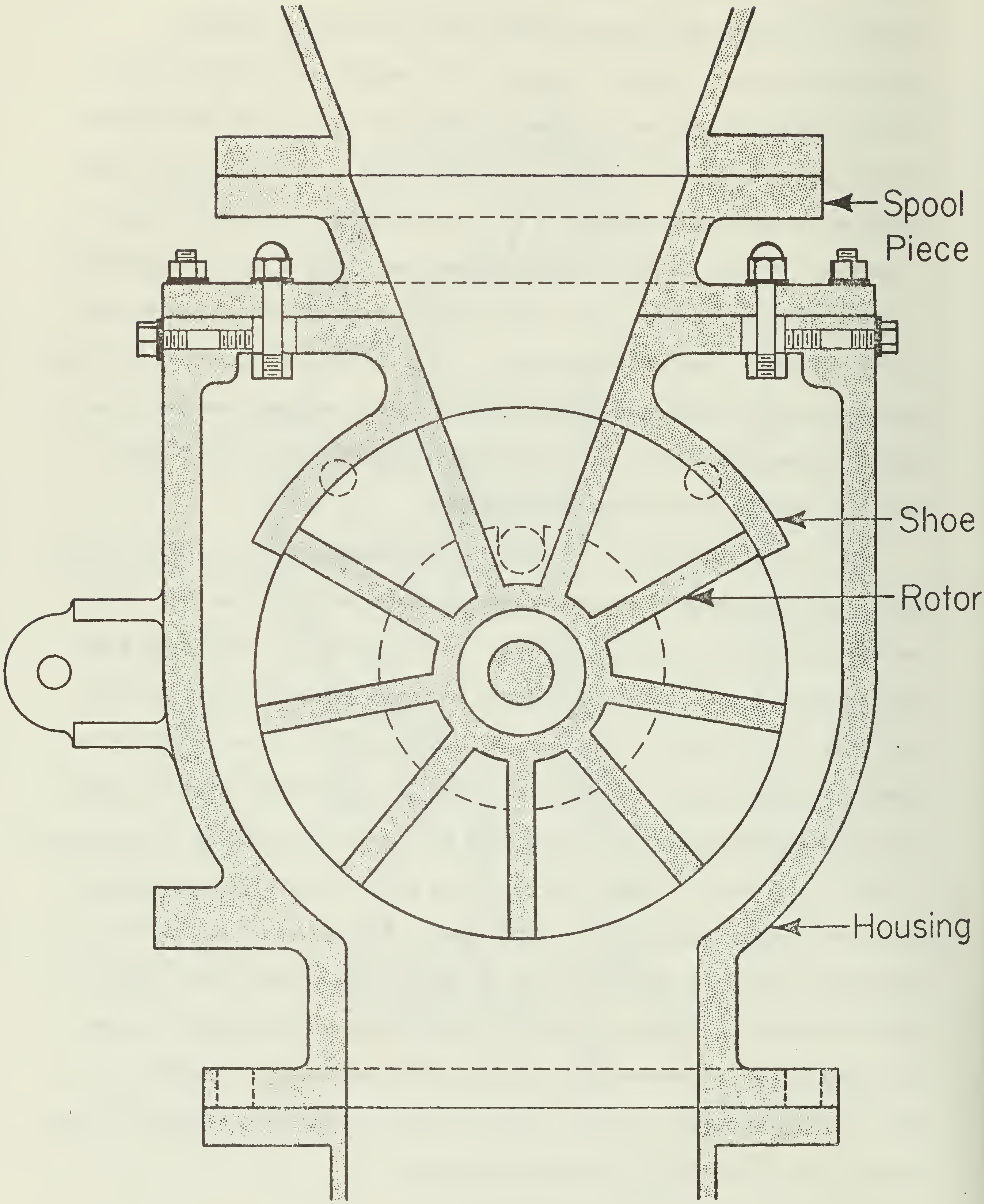

Figure 10 Rotary-Valve Feeder

When the system is operated under pressure, air enters at point B, is pulled through the compressor, pressurized, and piped to the coal pick-up valve. The coal-air suspension is pushed through the test piping and the coal is deposited in the receiver. Again, dust-laden air from the receiver is forced into the dust separator for cleanup followed by exhaust to the atmosphere.

Mine run coals of varying moisture and ash content and crushed to various sizes up to 2 inches (5.08 cm) are to be fed from the feed vessel into the 100 tph rotary valve feeder. Feed rate is controlled by a variable speed vibratory pan feeder that drops the coal by free-fall into the rotary valve feeder. With this method of feedering, the rotary valve feeder (Fig. 10), which will handle only small particles under normal choke-feeding conditions, can satisfactorily feed the larger 2-inch (5.08 cm) coal sizes.

FEED

The practices established in the design and operation of the pneumatic mine hoist [29] might be applied directly to the transportation system.

At the mine, material is transferred from the concentrator pile by means of a front-end loader and inlet to an RTL 200 Feeder is controlled by a Syntron vibrator unit. The complete system is operated by one man on the control console. An output up to 40 tph is achieved. Two hundred tph systems are commonplace. Materials with pieces as large as 3 inches (7.62 cm) can be handled. An alternate means is to have the mine cars unloaded onto a conveyor to the feeder.

For handling coal as mined, the vibrator feed, which includes large lumps, can be diverted from a grate which allows passage of 2 in. by 0 in. (5.08 cm by 0 cm) coal to a 10 by 15 jaw crusher set at 2 inches (5.08 cm).

A manual deflector at the discharge of the crusher into the inlet joins the coal from the vibrator grate with that diverted to the preparation unit.

SAFETY FEATURES

When the system is operating, the possibility of explosion in the pipelines is remote because the high transport velocities make if difficult or impossible for flames to propagate. In the vessels and separator, and during start-up and shut-down, velocities are lower and a remote possibility of explosion exists. As a safety precaution, inert gas is piped to various points of the system for purging to prevent fire and explosions during start-up and shut-down with sufficient inert gas being introduced to keep the O_2 concentration below 15 volume-percent.

The system can be designed to contain an explosion, according to approved practices in the installation and operation of pulverized fuel systems. Such practices require equipment to withstand explosion pressures up to 50 psig when pneumatically conveying powdered coal at absolute pressures up to one atmosphere. Equipment rated proportionately higher is needed for higher operating pressures. Vacuum operations require that all the main vessels be capable of containing explosive pressures up to 50 psig. The separator and the receiver are operated under low pressure, not exceeding 3 psig, which requires that they be designed to contain an explosive pressure of 60 psig. A 3 psig rupture disc limits the pressure in the receiver. This limited operating pressure can be maintained even with a 20 psig pressure at the coal pick-up point, since nearly all of this 20 lbs is used to transport the coal through the experimental pipeline. Both bessels are designed for 150 psig working pressures and have been previously operated at pressures up to 60 psig; the separator has been pressure tested satisfactorily to 60 psig.

FEASIBILITY OF PNEUMATIC PIPELINE TRANSPORT OF COAL

S. L. Soo
Professor of Mechanical Engineering
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801
Fellow, ASME

J. A. Ferguson
Formerly Graduate Research Assistant
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801;
Presently, Engineer with Caterpillar Tractor Co., Peoria, Illinois

S. C. Pan
Graduate Research Assistant
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

BSTRACT

Estimated national coal shipments of .5 billion tons per year (bty) (1.4 bilion metric tons per year) by 1985 call or an ability to triple the amount of oal presently shipped. The pneumatic ipeline is seen as compatible with rail and barges) for delivering to rail loadng facilities, distributing from termial points, and for gathering from several erminal points to supply a large gasifiation facility. Such mixed shipments can mprove the economy of rail operations. iven the trend toward the abandonment of ranch lines, this is desirable. The easibility of transporting coal particles the rate of tens of thousands of tons er day over distances of a few miles or ndreds of miles was studied.

ITRODUCTION

National coal shipments were 0.63 llion tons per year (bty) (0.57 billion tric tons per year) in 1947, fell to 045 bty (0.41 bmty) in the late 1960's, ad increased again to 0.63 bty (0.57 bty) in 1974. The estimate for 1985 is 12 to 1.5 bty (1.1 to 1.4 bmty). The aility to triple the amount of coal shipped must be found. An estimated capital otlay of $21 billion by 1985 will be reqired. The accuracy of the estimates is dpendent on the logistics of supply and te trend of technology. The tripling is nt expected to be uniform; for example, cal gasification might take 30 to 40 percnt of the coal produced, and regional cncentration is expected. Alternatively, te estimated 50-50 distribution of surfce and underground coal production might be altered[1,2]. Much of the currently planned eastward shipment of low sulfur western coal[3] will be modified significantly by any gasification processes which can successfully handle high sulfur Illinois coal. Moreover, any predictions should include estimates of technological evolutions.

The conventional way to ship coal is by rail--more specifically, by unit train. The logical questions are: Can the railroads, with current and planned rolling stock, handle a three-fold increase in shipments? Can we estimate the upper limit of rail capacity? Can other technologies contribute to the shipment of coal in an economic and compatible manner? The answer to all of these questions is "yes; with good planning and design."

Our study concerns the large scale transportation of coal including technical feasibility, energy system relations, and relative costs. Three modes were examined: rail, liquid slurry pipelines, and high pressure pneumatic pipelines. Barges, limited by the availability of waterways, are closely related to rail systems.

Optimization of coal transport, given current technology, is important because of its relatively low mine mouth cost and high transportation cost. The present study updates an earlier one[4] using current technical input, energy needs, systems, and trends.

Of the three systems, rail has been the most highly developed. Innovations

are limited by the weight of the existing system. A few slurry pipelines have been built. The one in operation[5] is characterized by large preparation and separation costs[6]. While it may receive coal from a rail shipment, its operation remains basically an alternative with large preparation and separation costs. The usefulness of high pressure pipelines is supported by recent experimental evidence. The latter has rendered some of the earlier conclusions[4] inaccurate. This study analyzes the feasibility of the pneumatic pipeline in a role supporting rail shipment. It also includes an economic analysis.

RAIL SHIPMENT

Our study uses Illinois coal as the basis for the first model[7]. It may be noted that even if the Illinois coal reserve is estimated to be as low as 140 billion tons (130 billion metric tons), via gasification and/or liquefaction, assuming 50 percent efficiency, this reserve equals 250 billion barrels of oil. This is twice the quoted reserve of Saudi Arabia and four times that of Iran. Illinois has an extensive rail network. The lines are old, and the current trend of abandonment (about 2,500 miles of branch lines) suggests the need for alternative transport and options.

In Illinois, where large increases in coal mining can be expected in the next decade, a ten-fold increase in south-north unit train shipments of over 250 miles (400 km) at 30 mph (48 km/hr) still yields a train density well within safe limits. To obtain an average speed of 30 to 50 mph (48 to 80 km/hr), significant upgrading of the current railroad is needed. Current maintenance and replacement spending does not insure an economical and reliable system. The cost of transporting coal in this Illinois model has been estimated[7]. Figure 1 gives a typical set of results of the unit cost of owning and operating unit trains for cases of new roadbed and rail, new rail and ties, and track upgrading alone. This unit cost is given for a range of construction costs, i.e., one time, twice, and five-fold increases over 1974 costs[8-14]. Several facts are shown in Fig. 1: The speed of the loaded trains, either 30 mph (48 km/hr) (more trains and less maintenance) or 50 mph (80 km/hr) (fewer trains and higher maintenance), does not significantly affect the cost; the yearly shipment capacity has a large influence except for the cases of track upgrading and is influenced by the other freight using the same track. The major fact shown in Fig. 1 is the high cost when new roadbed must be built, especially for shipping coal alone. Note that with new rails, the long distance hauling rate is 0.82¢/ton-mile (0.56¢/metric ton-km), higher than current long distance rates of 0.6¢/ton-mile (0.41¢/metric ton-km) (in this case: $7.92 \cdot 10^7$ tons/year ($7.1 \cdot 10^7$ metric tons/year), 250 miles (400 km), 50 mph with \$0.95 billion capital investment).

It appears that rail shipments with barges*, pneumatic pipelines, or both can improve the economy of rail operation. Given the trend toward the abandonment of branch lines, this is desirable. A pneumatic pipeline can be used either as a gathering line to supply a railroad unit train or to distribute rail shipments. The latter is significant in connection with the trend toward large coal gasification plants.

PNEUMATIC PIPELINES

Several recent findings point to the adequacy and versatility of pneumatic pipelines: (1) The pipe flow friction factors on which the 1962 Bureau of Mines estimates[4] were based were 10 to 50 times higher than those determined from recent experimental data[15] and experiments in England[16]. (2) The present study shows that a long distance pneumatic pipeline should be neither a vacuum suction system nor a 100-atm system. Only these two systems were considered in the 1962 report[4]. The optimum appears to be about 10 atm at a mass flow ratio of coal-to-air of nearly

*Barges are limited by the available water ways. Moreover, the quoted barge cost below 0.2¢/ton-mile does not include cost of maintaining water ways, locks, etc.

0. With this condition, coal occupies only 10 to 15 percent of the volume. Power failure, if it occurs, will temporarily close down the line but will not cause plugging of the pipes. A slurry line cannot be stopped; if there is a stoppage, the slurry must be dumped. (3) Pumping power requirements and pipeline costs are near those of a slurry pipeline. However, preparation costs amount to only the first stage crushing in a slurry facility, and the cost of separation is nil. (4) The pneumatic pipeline can be designed for short or long distance transport. It is compatible with rail either for delivering to loading facilities or for distributing from terminal points.

SYSTEM PARAMETERS

Of the three modes of transportation, information on railroad and unit train operation is extensive[7,17,18]. The slurry pipeline design is also known[19-21]. Thus, for an analysis and for comparison, only a few new basic parameters of pneumatic pipelines need to be clarified.

Basic Parameters

The present study shows that the pipeline pressure should be nearly 10 atm rather than a low of about 1 atm or a high of 100 atm. The selection of the pipeline pressure with respect to the states of a suspension is given in APPENDIX A.

System Formulation

In the systems formulation for the engineering design, the following features are noted:

Telescoping of a Pneumatic Pipeline. It has been shown by outlining the design procedures for a pneumatic pipeline (APPENDICES B,C) that, for transmission over distances of hundreds of miles, there is a choice between a small pressure ratio of pumping of, say 1.6:1 of inlet-to-outlet with short station spacing of less than 20 miles (32 km) (Fig. 2), and long station spacing of about 100 miles (160 km) with proper suspension velocity over the whole length following the design of Topper, et al.[23]. Because of the decrease in density (or increase in volume) of a gas as the pressure decreases along the pipeline, it is readily shown that long station spacing must be accomplished by increasing the pipe diameter via telescoping as the flow proceeds. In this way, the flow velocity is kept just high enough for the suspension but minimized the friction loss. Therefore, an optimum selection of various lengths of standard pipe of various diameters must be made. The design for telescoping the pipes is illustrated in Table 1. A typical mechanical system was illustrated by Topper, et al.[23] but the optimum design remains to be made in our continuing study. The range bracketed by the "lift parameter" covers the size distribution and the nature of the particles.

Safety and Wear of Pipes. In the pneumatic transmission of coal, it has been shown that, because of wear and safety, a large mass ratio of coal-to-air is desirable together with a high air density and an intermediate size of the coal particles; below 0.25 • 0 in. (0.64 • 0 cm) size for long distance transport and up to 2 • 0 in. (5 • 0 cm) for short distances of 3 to 5 miles (5 to 8 km). Details are given in APPENDIX D. Current practical experience can be found in pneumatic hoisting from mines[15,22].

Identification of System Parameters. Commonality of treatment among the transport modes is seen in Table 2. There are two basic groups of components: One, consisting of equipment at the supply and the receiving points, is concerned with capacity in tons/day of coal. The second group consists of transport modes which are related to both tons/day capacity and distance.

ECONOMICS

A common basis for comparison and costs estimation was used, via modification of procedures in Ref. 4. The output from the analysis is the total investment needed for any given capacity in tons/day (mt/day) and the cost in cents/ton-mile (¢/mt-km).

A. Slurry Pipeline

There are several published articles on slurry pipeline equipment[5] and pipeline costs. Our estimation, based on 1969 charges of 0.3 to 0.5¢/ton-mile of total[6] shows that for a capacity of 12,000 tons/day, equipment costs for a slurry pipeline facility would be \$80 million to \$120 million for preparation and separation, Table 3.

B. Pneumatic Pipeline

Table 3 illustrates pertinent engineering parameters for the comparisons. For a station spacing of 20 miles (32 km) at a 1.6:1 pressure ratio, the unit cost amounts to 0.4¢/ton-mile (0.28¢/mt-km) for an unburied pipe and 0.7¢/ton-mile (0.48¢/mt-km) for buried pipe. Table 3 also shows a comparison of typical pipeline system for natural gas and oil showing the availability of options for shipping coal to gasification plants for local use or to gasify coal to be pumped into gas pipelines.

C. Flexibility of Design

Flexibility of a pneumatic pipeline is seen over short distances. The planned 3-mile (5.6-km) pipeline for the Baldwin Power Plant of the Illinois Power Company is a case in point. The short distance permits a rather simple design with a compromise in power consumption and coal size. It appears feasible to transfer 18,000 tons/day (16,000 mt/day) of coal (below 1 in. (2.5 cm) size instead of an upper limit of 0.25 in. (6 mm) with a compressor of 2,500 hp and 17,000 scfm (482 m^3/min) at a maximum pressure of 4 atm. This allows for a gradient of 1.5 percent to a 300 ft (92 m) higher elevation at the delivery point from the starting point. The pipes will be unburied, 14 inches (36 cm) in diameter for the first 1.5 miles (2.4 km), 16 inches (41 cm) in diameter for the next mile, and 18 inches (45 cm) in diameter for the last mile ("telescoping"). Coal feeding is accomplished by alternately charging and discharging two bins with coal locks and valving. Unless otherwise cooled, the compressed air is initially at 350°F (176°C); hence, some wetness in the coal is readily accommodated. The pressure is nearly atmospheric at the delivery point.

A comparison has been made with a conveyor belt. The costs are high because of the short distance, i.e., 1.14¢/ton-mil (0.79¢/mt-km) for the pneumatic pipeline and 3.83¢/ton-mile (2.65¢/mt-km) for the conveyor belt, both unburied. However, the pipeline is still more economical than other means of transportation even over such a short distance. If the pipeline were buried, the cost would be 1.55¢/ton-mile (1.07¢/mt-km).

It takes less than four minutes for a batch of coal to clear the pipeline with a hold-up of 50 tons of coal in the pipe. Coal storage needs can be simplified because of this short response time.

D. Pneumatic Pipeline or New Rail

The desirability of substituting a pneumatic pipeline where new rail is to be built is readily seen in the case of coal shipments from the Black Mesa Mine to the Four Corners Power Plant[5]. The 273-mile (440-km) slurry pipeline was built as an alternative to adding 150 miles (240 km) of new rails to the 250 miles (400 km) of existing Santa Fe tracks. The decision is easily understood based on the following data:

Slurry Pipeline. 273 miles (440 km) at 1¢/ton-mile (0.69¢/mt-km) or \$2.73/ton.

Rail. 250 miles (400 km) at 0.6¢/ton mile (0.44¢/mt-km); 150 miles (240 km) at 1.0¢/ton-mile (0.69¢/mt-km), \$3.00/ton (\$3.3/mt). However, if a pneumatic pipeline were built to connect with the exist- rail:

Rail. 250 miles (400 km) at 0.6¢/ton mile (0.41¢/mt-km), 150 miles (240 km) pneumatic at 0.5¢/ton-mile (0.35¢/mt-kw), \$2.25/ton (\$2.47/mt).

Pneumatic Pipeline. 273 miles (440 km) at 0.5¢/ton-mile (9.35¢/mt-kw), \$1.17/ton (\$1.29/mt).

Items Rail and Pneumatic Pipeline (above)

emonstrate the usefulness of pneumatic . ipelines for coal shipment. The import- nt fact is that pneumatic pipelines, when roperly applied, help to complement rail ines, reduce railroad transportation osts, and make possible the upgrading of ailroads for general shipments.

UTURE GOALS

Use of pneumatic pipelines in coal ransportation can augment the railroads y serving as feeders from the mines and istributors to consumers. Pneumatic ipelines may also replace abandoned rail- oads for coal shipment. They can im- rove the profitability of the railroads, f owned or controlled by them, by further tilizing the right-of-way. The introduc- ion of a gasification facility can uti- ize pneumatic pipelines to gather coal rom several railroad terminals.

Where new rail is nonexistent and here only coal is to be handled, pneu- atic pipelines provide an economical eans of transport.

For moving coal over distances of ne mile or less, a conveyor belt system ay be the best choice; from 3 to 5 miles 5 to 8 km), a pneumatic pipeline carry- ng 2 • 0 in. (5 • 0 cm) coal, as mined, ill cost less than 1/3 the transport cost f a conveyor belt. For shipments of less han 100 miles, a pneumatic pipeline will e more than competitive with a unit train ecause the loading and unloading cost of he latter can be saved. Pipeline costs re even more favorable if new track must e built. Over still longer distances, nit trains might be the choice in con- ideration of the multiplication of dif- erent types of materials to be shipped.

HORT RANGE APPLICATIONS

Discussion with Peabody Coal Company nd Illinois Power Company personnel have ndicated to us that the present 3.5-mile 5.6 km) unit train supplying coal from he mine to the Baldwin Power Plant will e discontinued if other suitable means f transporting coal can be found. Our nalysis indicates that by using a telescoped pneumatic pipeline, the shipping cost over this short distance will be 1.14¢/ton-mile (0.79¢/mt-km) compared to 3.73¢/ton-mile (2.57¢/mt-km) by conveyor belt system. There is a definite interest in using the pipeline system once the finished design is available.

It appears that the most immediate applications of the pneumatic pipeline is that of a transport system for coal in conjunction with the use of the right-of-way of a railroad system. Supplying a large gasification facility from a railroad terminal by a pneumatic pipeline is desirable because the 0.25 • 0 in. (6 • 0 mm) coal size is correct for most gasification processes. Because of the speed of shipment in a pneumatic system, storage will be needed only at one end of the pipeline. This is significant considering the volume required for 60-day storage for a plant using 25,000 tons (23,000 mt) of coal per day. A slurry pipeline can also be supplied from a railroad; however, the requirement of a 14 by 325 mesh coal size for the slurry makes the dried coal unsuitable for feeding a gasification system.

ACKNOWLEDGMENT

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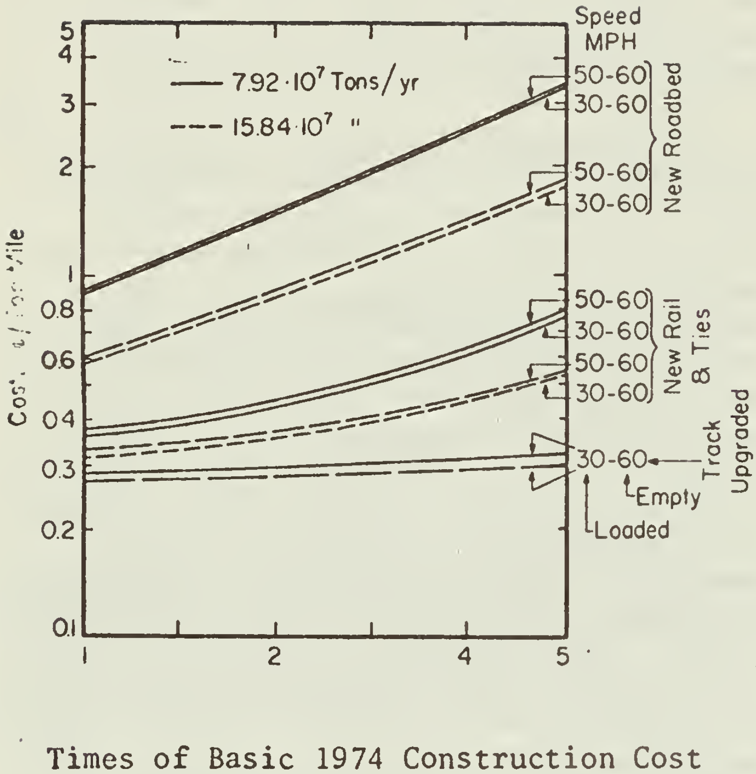


Figure 1 Cost of owning and operating rail for coal transportation for various ranges of construction cost (250 miles (400 km) one-way, 600 miles (960 km) of track, 10,350 tons (9,420 mt) of coal per train) (1¢/ton-mile = 0.684¢/mt-km; 1 ton per year = 0.91 mt/year; 1 mph = 1.6 km/hr).

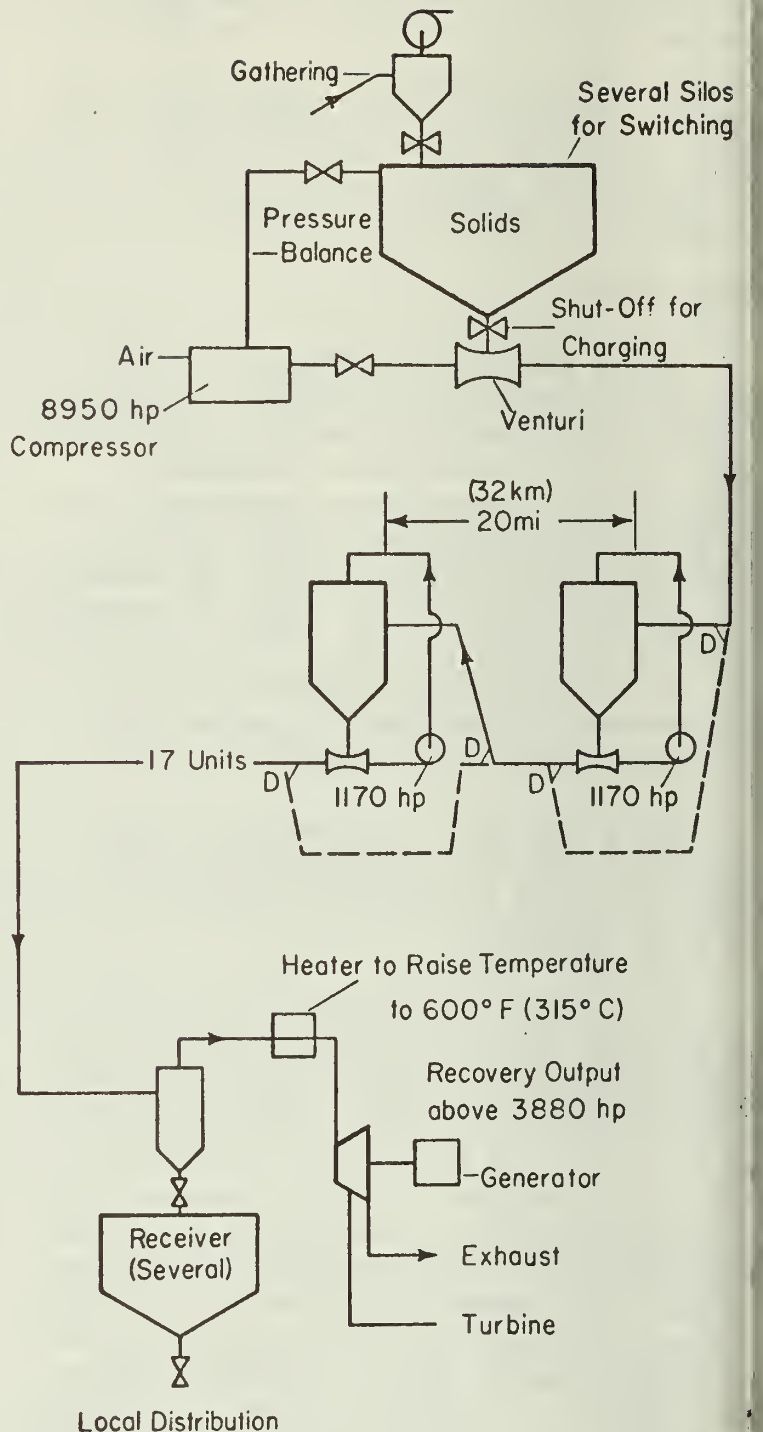
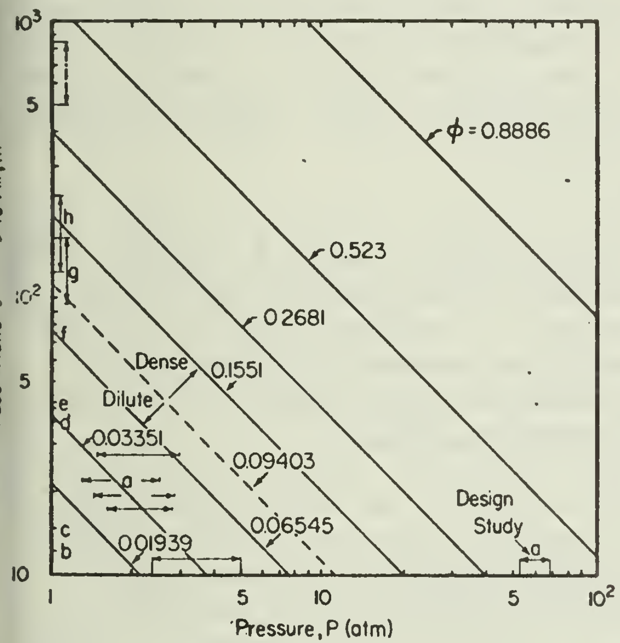


Figure 2 Typical high-pressure pneumatic pipeline system (example of a 400-mile (640 km) system for 10,000 tons (9,100 mt) of coal per day, D's denote diverter valves for station by-pass)

Volume Fraction Solid, ϕ	m^* P_{atm}	Interparticle Spacing/Size	Free Path/Size	Reference
				a 4
.8886	83060	0.838	0.2237(1)	b 15
.5230	12100	1.0	0.3186(2)	c 25
.2681	40440	1.25	0.4973	d 26
.1551	202.7	1.5	0.7163	e 27
.09403	114.6	---	1.00	f 28
.06545	77.32	2.0	1.273	g 29
.03351	38.28	2.5	1.989	h 30
.01939	21.83	3.0	2.865	i 31

(1)- Tetrahedral Piling (2)- Cubic Piling



igure 3 State of pneumatic suspension 30°F (25°C) air; sp. gr. of coal = 3: m* = lb coal/lb air; P = pressure, m)

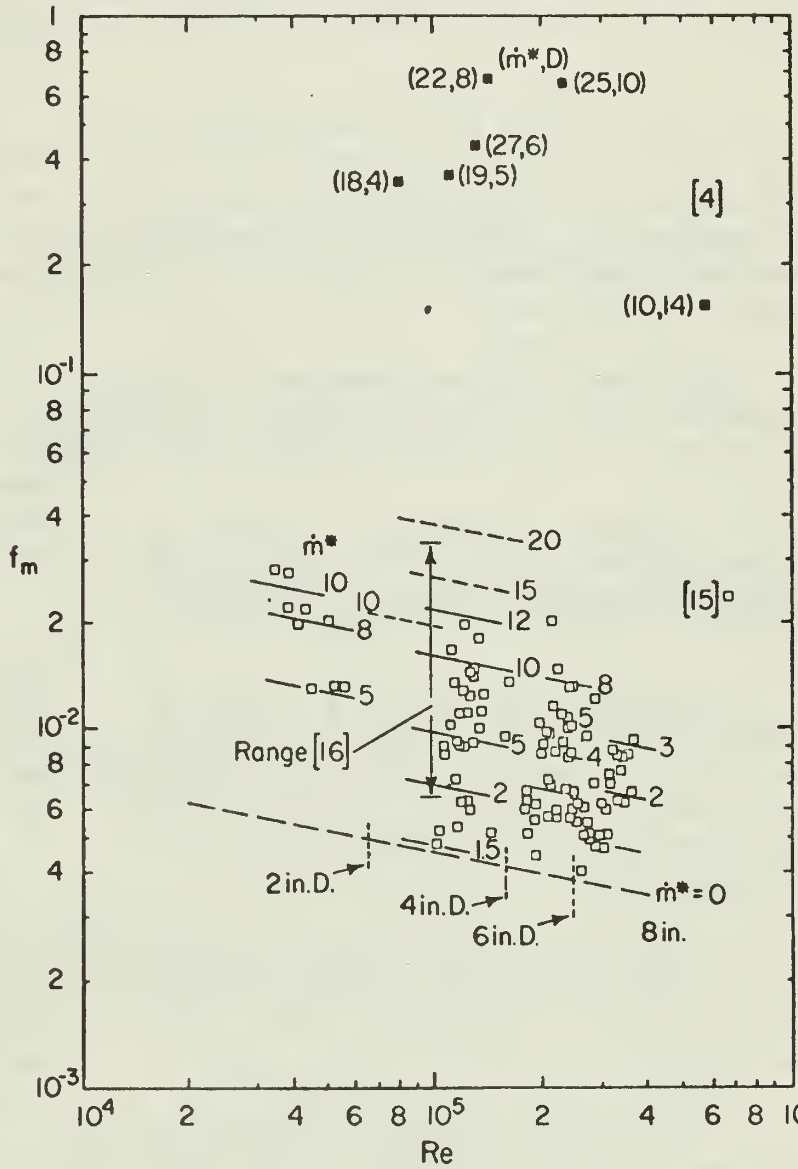


Figure 4 Friction factor (f_m) of pipe flow of coal suspension at various flow Reynolds numbers (m* = lb coal/lb air; D = pipe diameter, in. (1 in. = 2.54 cm)

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APPENDIX A: STATE OF A GASEOUS SUSPENSION

Studies on the subject of gaseous suspensions often refer to a suspension as "dense phase" or "dilute phase." Extremes of each are obvious; however, a sharp division is not defined.

For the flow of a suspension of mean solid particle size d_p in a pipe of diameter D, the parameters of interest are the material densities of the solid and as ρ_p and ρ, the mean velocities of phases u_p and u, the density of the particle cloud $\rho_p = \phi\ \rho_p$, and $\rho = \rho(1 - \phi)$ for the density of the gas in the mixture. ϕ being the volume fraction solid, we have the mass flow ratio of the phases:

$$\dot{m}^* = \rho_p\ u_p/\rho u \tag{A.1}$$

since $u_p < u$ in general [24] and $m^* > \dot{m}^*$.

Mean interparticle spacing is given by the number density of particles n:

$$n^{-1/3}/d_p = (\pi/6\phi)^{1/3} \tag{A.2}$$

The ratio of mean free path of particle-to-particle collision (λ) to interparticle spacing, given by

$$\lambda/n^{-1/3} = \phi^{-2/3}\ (36\pi)^{-1/3} \tag{A.3}$$

is a measure of freedom of movement of the particles, thus giving a measure of whether the phases are dense or dilute.

For coal particles in air, $\rho_p = 81.2$ lb_m/ft (sp. gr. = 1.3) at pressure P in atmospheres and temperature of 540°R (300°K), we have

$$\dot{m}^*\ P_{atm} = 1.104 \cdot 10^3\ \phi/(1 - \phi) \tag{A.4}$$

Moreover, the total flow rate of solid $\dot{m}_p$ is given by:

$$\dot{m}_p/(\pi/4)\ D^2\ u = 0.07355\ \dot{m}^*\ P_{atm} \tag{A.5}$$

which shows that the product $m^*\ P_{atm}$ is directly proportional to the throughflow for a given pipe diameter and flow velocity.

The relations given by Eqs. (A.2), (A.3), and (A.4) are incorporated in Fig.3 for various volume fractions of solid ϕ with P_{atm} from 1 to 100 atm and $\dot{m}^*$ of 10 to 10^3. Ranges of data[4,15,25-27] are shown for the "dilute phase" studies. Ranges are also identified for the "dense phase"[21-28]. Marked on the lines of Eq. (4) for constant ϕ are interparticle spacing/particle size, $\dot{m}^*\ P_{atm}$, and free path/interparticle spacing in the parentheses. Since the main difference between dilute and dense phase suspensions is in the freeom of movement of particles, we may assume the dividing line along the line of $\lambda/n^{-1/3} \simeq 1$ or $\phi \simeq 0.1$.

Figure 3 shows that, for a given state of suspension, increasing pressure will not increase the solid flow capacity. Hence, there is an optimum between the atmospheric pressure or vacuum and a high pressure of thousands of psia. This is because a high gas density calls for a lower suspension velocity, a relation to be treated in APPENDIX C.

Also noted in Fig. 3 is the range of the design study in the 1962 report of coal dust suspension in methane. It is seen, in spite of its low mass flow ratio (because of the high pressure), it actually corresponds to the most dense phase suspension ever subject to experiment. Since $u_p < u$, the actual m^* is expected to be much higher. The range of experiments on coal[4] is also shown in Fig. 3; the actual m^* is likely to have been much higher because of the unsteady flow produced by the feed system.

It will be shown that the advantages of high pressure diminishes beyond 10 to 20 atm of line pressure at $\dot{m}^*$ of 10 to 20.

APPENDIX B: FRICTION FACTOR

An extensive systematic effort to correlate the pressure drop in pipe flow with suspensions was that of Pfeffer[32]. Because of wide data scatter, no general correlation was possible; however, some trends were noted. His study included other results[25-27]. The method will be extended to recent results in the following.

For isothermal pipe flow of a gaseous spension in the system with pipe diameter length L, elevation H at one end, and tal flow of solids and air $\dot{m}_p$ and $\dot{m}_a$, spectively, the pressure drop dP over a ngth dx is given by:

$$dP = -4\ f_m (dx/D)\ [\rho(V^2/2)] - [d(\rho_m\ V^2)] - \rho_m\ g\ dh \qquad (B.1)$$

ere f_m is the friction factor of the xture of gas and solid; V, gas velocity; , density of mixture; $\rho_m = \rho + \rho_p$; g, e gravitational acceleration for ρg is $_m/ft^3$ (ρ in kg/m); and dh, the rise in evation over dx. In Eq. (B.1), the rst term on the right-hand side is pres- re drop due to friction; the second term, celeration; and the third term, the avity effect due to elevation. Note, ss flow G is given by

$$\rho_1\ V_1 = \rho_2\ V_2 = \rho\ V = \dot{m}_a/(\pi/4)\ D^2 = G \quad (B.2)$$

bscripts 1 and 2 denote inlet and out- t, respectively.

The friction factor of turbulent pipe ow of a simple fluid, e.g. air, in a ooth pipe is given by

$$f_a = 0.046/Re^{0.2} \qquad (B.3)$$

ere the Reynolds number Re is given by

$$Re = D\ \rho\ V/\mu = DG/\mu \qquad (B.4)$$

ere μ is the viscosity of gas.

For small changes in pressure or nsity of the gas phase, Eq. (B.1) is in- tgrated as an incompressible fluid.

$$P_1 - P_2 = 4f_m\ (L/D)(G^2/2\rho) + (1 + \dot{m}^*) \cdot \rho\ (V_2^2 - V_1^2) + (1 + \dot{m}^*)\ \rho H\ g \qquad (B.5)$$

r small ϕ, $P \simeq \overline{P}$ of the gas. For large anges of pressure, P_1 to P_2, of the gas, mpressibility is accounted for via in- tgration to:

$$[1 - (P_2^2/P_1^2)] = 4f_m(L/D)\ (\rho_1^2\ V_1^2\ RT/P_1^2) + (1 + \dot{m}^*)(2G^2\ RT/P_1^2)\ \ln\ (P_1/P_2) + (1 + \dot{m}^*)\ (2\bar{P}^2 g\ H/RT\ P_1^2) \qquad (B.6)$$

for inlet pressure P_1 and velocity V_1; $\overline{P} = (P_1 + P_2)/2$.

These relations were used to evaluate the data in Table IV-3 of Ref. 4, and Eq. (B.2) was used to evaluate the data of Konchesky[15] for straight runs of pipes because of the small change in pressure. Data for f_m/f_a versus Re are shown in Fig. 4 with ranges of $\dot{m}^*$ and pipe sizes indicated. Note that for similar $\dot{m}^*$ and Re, tests[4] give f_m/f_a values of one to two orders of magnitude larger than those obtained from the Konchesky tests which were based on vacuum suction of coal 4·0 in. (10·0 cm) in size. This comparison confirms the suggestion that, because of unsteady flow, m* had reached much higher values than the reported averages[4]. Konchesky, et al., also concluded that the size of coal has an insignificant effect for $d_p < (1/3)$ D. Experiments by Sproson, et al.[33], show ranges similar to Konchesky's.

Konchesky's results appear to be adequately correlated by the relation proposed by Dogin and Lebedev[25] according to

$$f_m = f_a + A(d_p/D)^{0.1}\ Re^{0.4} \cdot Fr^{0.5}\ (\bar{\rho}_p/\rho)\ \dot{m}^* \qquad (B.7)$$

where Fr is the Froude number

$$Fr = V^2/g\ D \qquad (B.8)$$

which accounts for the gravity effect in horizontal pipe flow. A is a parameter depending on the roughness of the pipe. For the Konchesky data,

$$A \simeq 2 \cdot 10^{-7} \qquad (B.9)$$

instead of $10^{-6} < A < 2.10^{-6}$ proposed by Dogin, et al., $A = 2.10^{-6}$ seems to correlate data on coal dust[4].

Another correlation[34] to account for the effect of mass flow of solid and density ratios of phases can be expressed in the form

$$f_m = f_a + (\pi/8)\ \dot{m}^* \ (\bar{\rho}_p/\bar{\rho})^{1/2}\ \psi \quad (B.10)$$

ψ was given as a function of Re having a value below 10^{-5} for Re > 35,000; however, calculations from Konchesky's data give $\psi \simeq 10^{-4}$.

Pfeffer[13], coding various sources of data, suggested:

$$f_m = f_a\ (1 + \dot{m}^*)^{0.3} \quad (B.11)$$

without regard to other factors. This correlation tends to give an optimustic estimate of pressure drop, and we shall treat it as the lower bound of f_m.

Extensive measurements were made on the transport of pulverized coal through pipes[35]. Unfortunately, no data were taken on a straight run of pipe for comparison; the records on bends were archaic. His use of gamma-ray detection of sedimentation appears useful, however.

APPENDIX C: SUSPENSION VELOCITY

Equation (B.6) suggests the use of the lowest possible suspension velocity in turbulent flow to achieve a small pressure drop. This lowest velocity must be high enough to prevent settling of solids, especially in horizontal pipe flow, thus maintaining steady flow at low friction loss. There is extensive visual evidence of different states of suspension before plugging would occur[36], and the criteria of saltation[37,38] were analyzed.

Most of the basic studies on the lift force on a particle in a gas solid suspension treated cases of particle size smaller than the thickness of the laminar sublayer in a turbulent flow[39,40]. These do not apply to the case of transport of large particles above millimeter size. In the latter case, the correlation of Zenz[38] can be extended as follows for β > 10:

$$\alpha \simeq C_1\ \beta^s \quad (C.1)$$

where $C_1 \simeq 0.90$ for spherical particles and 0.5 for angular particles; $s \simeq 0.45$, and

$$\beta = d_p/\Delta \equiv d_p\ \{3\nu^2/4g \cdot [(\bar{\rho}_p/\bar{\rho}) - 1]\}^{-1/3} \quad (C.2)$$

and

$$\alpha = u_s/\omega\ D^{0.5} \equiv u_s\ \{(4g\nu/3) \cdot [(\bar{\rho}_p/\bar{\rho}) - 1]\}^{-1/3}\ D^{-0.5} \quad (C.3)$$

for D in inches; other groups are dimensionless. Here ν is the kinematic viscosity of the gas; g, gravitational acceleration; and u_s, minimum suspension velocity of a single particle. For the mass flow rate of particles $\rho_p u_p'$, Zenz suggested, for minimum transport velocity u', a relation:

$$\dot{m}_p/(\pi/4)\ D^2\ \rho_p = 0.7\ k(s)^{1.5} \cdot [(u_p'/u_s) - 1] \simeq \dot{m}^*\ u_p'\ (\bar{\rho}/\bar{\rho}_p) \quad (C.4)$$

for u_p' in fps (or m/sec). His results are comparable to those obtained by Thomas[41]. Correlation of the Konchesky data[15] with the above relations on suspension velocity shows that the distribution in particle size of coal in his tests is represented by $d_p \simeq$ 1/16 in. (1.6 mm) with flow velocity V above the value of u' obtained from Eq. (C.4). In Eq. (C.4), the suspension parameter ranges from 1 to 10 which is consistent with the large pipe data of Konchesky[15] and water slurry suspension velocities[5].

PRESSURE DROP AND THE NEED FOR TELESCOPING PIPES

Equation (C.6) shows that when the operating pressure of a pneumatic pipeline is high, the pressure drops due to acceleration and elevation, in hundreds of feet for a pipeline of miles (km) in length, become minor and the main pressure drop is that of friction:

$$[1 - (P_2^2/P_1^2)] = 4f_m\,(L/D)\,(V_1^2/RT_1) \qquad (C.5)$$

›r an isothermal pipeline with velocity
 and temperature T_1 at the inlet. The
ıs temperature T tends to a constant
ılue for a long distance pipeline.

When small station spacing is allow-
›le, a subsonic ejector feed system may
› used. For air, the pressure ratio is
ıen limited to $P_2/P_1 \geq 0.5457$, and a
ɜasonable pumping pressure ratio may be
.6:1. For V_1 greater than or equal to
ınimum suspension velocity at inlet tem-
ɜrature T_1, the only quantity in
ı. (C.5) that is affected by pressure
; the friction factor which determines
:ation spacing L. It is readily shown
ıat such a design usually limits station
›acing to less than 20 miles (32 km).

Equation (C.5) also shows that as
›ng as a uniform pipe diameter D is used,
ırge differences in pressure P_1 and P_2
: the inlet and outlet will not neces-
ırily increase the length L because of
ıe large pressure drop caused by in-
ɾeased flow velocity at low air density
; the pressure is lowered, thus causing
ɾeatly increased friction loss. This
ıggests telescoping the pipe diameters
; the pressure is lowered subject to the
ɜquired suspension velocity. With such
 design, a pressure ratio of 10:1 will
ɜrmit station spacing of approximately
)0 miles. In such a case, a pressurized
ɜed of solids and an injection system
ıst be used at each station as in the
ɜsign of Topper, et al.[23]

Since we are to choose among standard
ɪpe sizes, the design steps for given $\dot{m}^*$,
, and T are worth mentioning. By de-
ıning

$$\gamma = 4\dot{m}_p/\pi D^2\,\bar{\rho}_p\,\omega \qquad (C.6)$$

ıd

$$A^{-1} = \dot{m}^*(12)^{0.5}\,C_1\,\beta^s\,(\bar{\rho}/\bar{\rho}_p) \cdot (4\dot{m}_p/\pi\,\rho_p)^{1/4} \qquad (C.7)$$

ɪuation (C.4) with Eqs. (C.1) and (C.3)
ɪve

$$\gamma[A\gamma^{1/4}\,\omega^{1/4} - (\omega/0.7)\,kS^{1.5})] = 1 \qquad (C.8)$$

which is solved for γ, given from Eq. (C.6) and $V_1 = u_p'$. For each P_1 (selected along a geometric scale), we get V_1 and D. Interpolation for the squares of standard pipe diameters D (ID) gives us a new set of P_1, V_1, from which we compute Re and f_a from Eqs. (B.3) and (B.4) and f_m for the case under consideration. Since P_2 in Eq. (C.5) is P_1 of the next pipe size, the length L of each branch of diameter D is given by Eq. (C.5).

APPENDIX D: BREAKAGE, WEAR, AND SAFETY

A natural concern when considering pneumatic conveyance of solids is wear of components and deposition of fines due to breakage of coal in the system. Initially, breakage of coal is less likely at high air pressures than at atmospheric pressure because of the higher density of the gas which results in a reduced velocity of impact of the particles on a surface. It is readily shown that at 10 atmospheres of pressures, the impact velocity of a particle for a given flow velocity and geometry is 1/3 that at atmospheric condition. This is because the resistance to relative motion of solid particles is proportional to the product of density of air and the square of relative velocity. The resulting intensity of impact will be $(1/3)^{6/5}$ or 1/4 that at atmospheric conditions[24]. Hence, at prevailing temperatures, all wear and deposition due to fines will be reduced. Deposition will also be less due to reduced area and intensity of contact. Magnitude of wear, and the provisions needed to reduce deposition, remain to be determined via model testing. The amount of metal removed by impact is nearly 1/9 that at atmospheric condition[24,42]. Because of the above argument, it is postulated that cyclone wear will be less at elevated pressures than at atmospheric pressure.

Recent work[43] has shown that when coal dust suspended in air with a 1:1 mass ratio was ignited in a tube, fines below 20 microns were ignited but the resulting flame was smothered by coarser

coal particles. Since our proposed system handles coal chips below 0.25 in. (6 mm) in size with a 10:1 coal-to-air mass ratio, it has been demonstrated in practice that a pneumatic pipe transport system for underground coal haulage is conducive to safer and more healthful mines than by conventional means[15].

Table 1 Telescoping Pnuematic Pipelines for Long Distance Transport (0.25 x 0 in. (6 x 0 mm) Coal (13,00 Tons per day (11,800 mt/day), 17 atm Inlet Pressure, 1 atm Outlet Pressure)

Standard Pipe Schedule 20 Nominal Diameter		Inside Diameter		Lift Parameter 7.5				Lift Parameter 10			
				Mass Flow Ratio 10		Mass Flow Ratio 15		Mass Flow Ratio 10		Mass Flow Ratio 15	
in.	cm	ft	m	miles	km	miles	km	miles	km	miles	km
8	20.4	0.625	0.181								
10	25.4	0.791	0.241			1.74	2.79				
12	30.5	0.958	0.292			9.15	14.64			16.38	26.21
14	35.4	1.281	0.394	14.59	23.34	6.42	10.27			14.38	23.01
18	45.6	1.448	0.443	16.52	26.43	5.63	9.01	26.06	41.70	11.70	18.72
20	51.0	1.604	0.490	23.51	37.62	8.06	12.90	44.87	71.79	15.32	24.51
24	61.0	1.938	0.492	19.98	31.97	4.40	7.04	40.10	64.16	12.57	20.11
30	76.0	2.417	0.739	12.61	20.18	9.94	15.90				
Totals:				87.21	139.54	43.36	72.55		177.35	70.35	112.56

Table 2 Parameters for Coal Transport System

Supply Point	Transport Facility	Receiving Point
Primary Parameters Tons/Day	Tons/Day and Distance	Tons/Day
Common to All: (1) Mine, (2) Loader, (3) Storage, (4) Labor	(1) Terrain, (2) Labor, (3) Power and Fuel	(1) Utilization, (2) Labor
Railroad: (5) Loading Facility, (6) Supplies	(Speed) (4) Rails, (5) Locomotives, (6) Cars, (7) Stations	(3) Unloading Facility, (4) Storage
Slurry Pipeline: (5) Slurry Preparation, Mills, Storage Tanks, Agitators, (6) Pumping, (7) Water Supply, (8) Supplies	(Flow Velocity) (4) Pipeline, (5) Pumping Stations, (6) Supplies	(3) Stirred Storage, (4) Separation Facility Centrifuge to Coal and Water, Water Disposal
Pneumatic Pipeline: (5) Crusher, (6) Injection Bins, (7) Compressors, (8) Supplies	(Flow Velocity) (4) Pipeline, (5) Pumping Stations, (6) Supplies	(3) Receiver Bins

Table 3 Comparison of High Pressure Transmission of Coal in Air Suspension with Other Systems

Form	Gas	Oil	Coal (Air Suspension)	Coal (Water Slurry)
Heating Value	1,000 Btu/ft^3 (3.73 10 J/m)	18,500 Btu/lb (43,000 J/g)	12,000 Btu/lb (27,000 J/g)	12,000 Btu/lb (28,000 J/g)
Flow	240 mmscfd (6.8 mmscmd)	37,000 bbl/day	10,000 tons/day (9,000 mt/day)	10,000 tons/day (9,000 mt/day)
Line Pressure	68 atm		15 atm	68 atm (Heavy Pipe Costs More)
Energy Density, Btu/ft	6.8×10^4 (2.54×10^9 J/m)	9.68×10^5 (36.1 10^9 J/m^3)	7×10^4 (2.61×10^9 J/m^3)	5×10^5 (2.24×10^9 J/m^3)
Practical Flow Velocity, fps (m/sec)	30 to 60 (9 to 18 m/sec)	5 to 10 (1.5 to 3 m/sec)	20 (6 m/sec)	5 (1.6 m/sec)
Pipe Diameter, in. (cm)	16 to 12 (40 to 30)	10 to 7 (25 to 18)	14 in. (35 cm)	14 in. (35 cm)
Power Requirement, hp	25,300	25,850	24,450	20,240
Volume Fraction Solid			4.5% (to 9.1%)	32.1%
Cost			0.4 to 0.7¢/ton-mile (0.28 to 0.48¢ per mt-km)	0.7 to 1.1¢/ton-mile (0.18 to 0.76¢/mt-km)

COAL TRANSPORTATION

S. L. Soo

with

A. J. Ferguson, S. C. Pan and S. R. Sias

I. Introduction

In a panel discussion on "The Role of Fossil Fuels in Achieving Energy Independence," it was reported that national coal shipments were 0.63 billion tons per year(bty) in 1947, fell to 0.45 bty, and increased to 0.63 bty in 1974. The estimate for 1985 is 1.2 - 1.5 bty. The ability to triple the amount of coal shipped must be found. An estimated capital outlay of $21 billion by 1985 will be required to do this. But the accuracy of the estimates is dependent on the logistics of supply and the trend of technology. For example, coal gasification might take 30 to 40 percent of the coal produced. Or, the estimated 50-50 distribution of surface and deep mine coal production might be altered (Ref. 25,27). Much of the currently planned shipment of low sulfur western coal eastward (Ref. 26) will be significantly modified by any gasification process which can successfully handle high sulfur Illinois coal.

The conventional way of shipping coal is by rail. In recent years more specifically by unit train. The logical questions are: Can the railroads with current and planned rolling stock handle a three fold increase in shipments? Can we estimate the upper limit of rail capacity? Can other technologies contribute to the shipment of coal in an economic and compatible manner?

Studies under the present NSF contract of large scale transportation of coal have been initiated; including technical feasibility, energy system relations, and relative costs. Three modes are examined: rail, liquid

slurry pipeline, and high pressure pneumatic pipeline. Barges, limited by the availability of waterways, are discussed in relation to rail systems.

Optimization of coal transport, given current technology, is important because of its relatively low mine mouth cost and high transportation cost. The present study updates an earlier one by the Bureau of Mines (Ref.1 1962) using current technical input, energy needs, systems, and trends.

Of the three systems, rail has been highly developed. Innovations are limited by the weight of the existing system. Therefore, our study uses rail as a standard for an economic analysis of coal transport by other modes. A few slurry pipelines have been built; one is in operation (Ref. 2). Its status has advanced beyond basics. Therefore, the present study concerns its engineering and economics. The high pressure pneumatic pipeline is supported by recent experimental evidence. This has rendered some of the earlier (1962 Bureau of Mines) conclusions inaccurate. Currently, basic information is being assembled for designing an engineering system. This will be followed by an economic analysis.

This study uses Illinois coal as the basis of the first model. It may be noted that even if, at current prices, the Illinois coal reserve is estimated as low as 140 billion tons, via gasification and/or liquefication assuming only 50 percent efficiency the reserve equals 250 billion barrels of oil. This is twice the quoted reserve of Saudi Arabia and four times that of Iran. Illinois has an extensive rail network. The lines are old and the current trend of abandonment, about 2,500 miles of branch lines, suggests the need for transport alternatives and options.

II. Summary of Findings

A. Rail

1. In Illinois, where large increases in coal mining can be expected in the next decade, a ten-fold increase in south-north unit train shipments of over 300 miles at 40 mph still yields a train density well within safe limits.
2. To obtain an average of 40 mph, significant upgrading of the current railroad system is needed. Current maintenance and replacement spending does not insure an economic and reliable system.
3. In order to triple the amount of coal shipped, locomotives of 10,000 hp unit capacity are desirable for economic operation.
4. Mixed rail shipments, with barge, pneumatic pipeline, or both, can improve the economy of rail operation. Given the trend toward the abandonment of branch lines this is desirable. A pneumatic pipeline can be used either as a gathering line to supply a railroad unit train or to distribute rail shipments. The latter is significant and in connection with the trend toward large coal gasification plants.

B. Slurry Pipelines

1. The economy of pumping a slurry over a distance is counterbalanced by the cost of preparation and separation equipment and their operation (Ref. 2). For a slurry system with 12,000 - 18,000 tons/day capacity, the equipment cost alone is calculated at $80 million to $120 million (Ref. 3).
2. A slurry line is suitable only for distances of above 200 miles. The optimum remains to be determined, but at 270 miles, preparation

and separation cost is 30 to 50 percent of the total shipping charge. This assumes no problem in the disposal of transport water and a zero cost of water at the inlet.

C. Pneumatic Pipelines

1. The pipe flow friction factors on which the 1962 Bureau of Mines estimates (Ref. 1) were based were 10 to 50 times higher than those determined from recent experimental data at the U. S. Bureau of Mines (Ref. 4), and experiments in England (Ref. 23).

2. The present study shows that a long distance pneumatic pipeline should be neither a vacuum suction system nor a 100 atmosphere system. Only these two were considered in the 1962 report (Ref. 1). The optimum appears to be about 10 atm. at a mass flow ratio of coal to air of nearly 10. At this condition coal only occupies 10 to 15 percent of the volume. Economic pumping can be achieved and temporarily closing down the line will not cause plugging of the pipes. A slurry pipeline cannot be stopped. If there is a stoppage, the slurry must be dumped.

3. Pumping power requirements and pipeline costs are near those of a slurry pipeline, but preparation costs amount to only the first stage crushing of a slurry facility and the cost of separation is nil.

4. The pneumatic pipeline can be designed for short or long distance transport. It is compatible with rail either for delivering to the loading facilities or for distributing from the terminal points.

III. Research Program

Of the three modes of transportation, the information on railroad and unit train operation is extensive (e. g. Reference 28 & 29). The slurry pipeline design is also known (Ref. 30, 31, 32). Thus, basic information is available for most elements of these transportation systems. Only a few items remain to be clarified.

A. Friction factors of a pneumatic suspension.

The conclusions on the pneumatic pipeline in the 1962 study (Ref. 1) were based on an unsteady flow of pulverized coal and cement in large pipes (14" dia.). This resulted in friction factors of 10 to 50 times those derived from recent Bureau of Mines measurements. (Appendix 1) Another source of data for the 1962 study was an extrapolation from pipes smaller than 1.38" dia. This led to the conclusion that energy consumption in pneumatic transport was unacceptable. The present study correlated the pipe friction factor from recent data and a range of suspension velocity to give a realistic estimation of the pressure drop and pipe size. It was also shown that the operating pressure and mass ratio of coal to air must be properly selected via optimization procedures.

The result of this study shows that the pipeline pressure should be nearly 10 atmospheres rather than a low of about one atmosphere or a high of 100 atmospheres.

Another basic topic is the injection of coal from bins into pipelines.

B. System Formulation

In the systems formulation, we are closing the gaps in engineering design illustrated in the following items:

1. Telescoping of a pneumatic pipeline. It has been shown from outlining the design procedures for a pneumatic pipeline that, for transmission over distances of hundreds of miles, there is a

choice between small pressure ratio of pumping of say 1.6 of inlet to outlet with short station spacing of less than 20 miles, and long station spacing of about 100 miles with proper suspension velocity over the whole length. Because of the great changes in density of a gas with great alterations of pressure, it is readily shown that long station spacing must be accomplished by telescoping the pipe diameter as the flow proceeds. Therefore, an optimum selection of various lengths of standard pipe of various diameters must be made. This is illustrated in Appendix 2.

2. Safety and wear of pipes. In the pneumatic transmission of coal it has been shown that because of wear and safety, a large mass ratio of coal to air is desirable together with a large air density and an intermediate size of coal particles; below 1/4-xO" size for long distance transport and up to 2-xO" for short distances of 3 to 5 miles. Details are given in Appendix 3.

3. Identification of system parameters. Commonality of treatment among the transport modes is seen in Table 1. There are two basic groups of components; one consisting of equipment at the supply and the receiving points, is concerned with capacity in tons/day of coal; the second group consists of transport modes which are related to both tons/day capacity and distance.

C. Economics

To arrive at a common basis for comparison and costs estimation, an outline of common steps in the analysis is illustrated in Appendix 4. The output from the analysis is the total investment needed for any given tons/day capacity, and the cost in ¢/ton-mile.

1. Unit train. The results of an analysis of a unit train operation is illustrated in Appendix 5. It is seen that with new rails, the long distance hauling rate is .82¢/ton-mile; higher than

Table 1

Parameters for coal transport systems

SUPPLY POINT	TRANSPORT FACILITY	RECEIVING POINT
(Primary Parameters) (tons/day)	(tons/day and distance)	(tons/day)
Common to all:		
1. Mine	1. Terrain	1. Utilization
2. Loader	2. Labor	2. Labor
3. Storage	3. Power and fuel	
4. Labor		
Railroad:	(Speed)	
5. Loading facility	4. Rails	3. Unloading facility
6. Supplies	5. Locomotives	4. Storage
	6. Cars	
	7. Stations	
Slurry pipeline:	(Flow velocity)	
5. Slurry preparation	4. Pipeline	3. Stirred storage
Mills	5. Pumping stations	4. Separation facility
Storage tanks	6. Supplies	Centrifuge to
agitators		coal and water,
6. Pumping		Water disposal
7. Water supply		
8. Supplies		
Pneumatic pipeline	(Flow velocity)	
5. Crusher	4. Pipeline	3. Receiver bins
6. Injection bins	5. Pumping stations	
7. Compressors	6. Supplies	
8. Supplies		

current long distance rates of 0.6¢/ton-mile (in this case: 7.92×10^7 tons/yr, 250 miles, 50 miles/hr., with $.95 billion capital investment).

2. Slurry pipeline. There are several published articles on slurry pipeline equipment (Ref. 2) and pipeline costs. Our estimation, based on 1969 charges of .3 to .5¢/ton-mile, without preparation and separation charges, and .7 to 1.1¢/ton-mile total (Ref. 3), shows that, for a capacity of 12,000 to 18,000 tons/day, equipment costs for a slurry pipeline facility would be $80 million to $120 million as computed according to Appendix 4.

3. Pneumatic pipeline. Optimum design remains to be made after completing the engineering system optimization.

Table 2 illustrates pertinent engineering parameters for comparision. The designs have not been optimized at this stage. A computer model is being formulated.

Table 2 Comparison of High-Pressure Transmission of Coal in Air Suspension with Other Systems*

Form	Gas	Oil	Coal (Air Suspension)	Coal*** (Water Slurry)
Heating Value	1,000 Btu/ft^3	18,500 Btu/lb	12,000 Btu/lb	12,000 Btu/lb
Flow	240 mmscfd**	37,000 bbl/day	10,000 tons/day	10,000 tons/day
Line Pressure, psig	68 atm		15 atm	68 atm (heavy pipe costs more)
Energy Density, Btu/ft^3	6.8×10^4	9.68×10^5	7×10^4 (to 1.4×10^5)	5×10^5
Practical Flow Velocity, fps	30 to 60	5 to 10	20 to 60 ft/sec	8 ft/sec
Pipe Diameter, inches	16 to 12	10 to 7	12 inches	11 inches
Power Requirement, hp	25,300	26,850	24,450	20,240
Volume Fraction Solid			4.5% (to 9.1%)	32.4% (particles nearly one 'diameter' apart-- greater danger of clogging) Volume fraction solid

* Based on an equivalent 10^{10} Btu/hr transmitted, over 400 miles distance

** Million standard cubic feet per day

*** Converted from Black Mesa Pipeline data

IV. Future Goals

A. Use of pneumatic pipelines in coal transportation to augment the railroads by serving as feeders from the mines and distributors to consumers. Pneumatic pipelines may also replace abandoned railroads for coal shipment. They can improve the profitability of the railroads, if owned or controlled by them, by further utilizing the right of way. The introduction of a gasification facility can utilize pneumatic pipelines to gather coal from several railroad terminals.

B. Where new rail is nonexistent and where only coal is to be handled, pneumatic pipelines provide an economical means of transport.

C. The present railroad system has ample shipping capacity over its length at reasonable speeds of 40 to 50 mph average. Therefore, new outlay in upgrading of road, is vital and worthwhile. If these measures can be carried out, increases in the number and size of locomotives and unit train cars will be needed and justified.

D. Continuing study will further quantify the above and the system design. For example: for moving coal over distances of a mile or less, a conveyor belt system may be the best choice; from 3 to 5 miles, a pneumatic pipeline carrying 2-x0" coal as mined will cost less than 1/3 the transport costs of a conveyor belt. For shipments of less than 100 miles, a pneumatic pipeline will be more than competitive with a unit train because the loading and unloading cost of the latter can be saved. Pipeline costs are even more favorable if new track must be built. Over still longer distances, unit train might be the choice in consideration of the number of types of materials to be shipped.

V. Utilization to date and future utilization plans

A. Discussions with the Peabody Coal Company and the Illinois Power Company have indicated to us that the present 3.5 mile unit train supplying coal from the mine to the Baldwin Power Plant will be discontinued if other suitable means of transporting coal can be found. Our analysis indicates that by using a telescoped pneumatic pipeline, the shipping cost over this short distance will be 1.14 ¢/ton-mile compared to 3.83¢/ton-mile by conveyor belt system. There is definite interest in using the pipeline system once the design is available.

B. It appears that the most immediate application of the pneumatic pipeline is that of a conveyor system for coal transport in conjunction with use of the right of way of a railroad system. Supplying a large gasification facility from a railroad terminal by a pneumatic pipeline is desirable because the 1/4-x0" coal size is right for most gasification processes. Because of the speed of shipment in a pneumatic system, storage will be needed only at one end of the pipeline. This is significant considering the volume of a 60 day storage for a plant using 25,000 tons of coal per day. A slurry pipeline can also be supplied from a railroad, but the requirement of a 14 x 325 mesh coal size for the slurry makes the dried coal unsuitable for feeding a gasification system.

C. In the future is a computer program for optimizing coal supply sources for gasification. For example: once a gasification process for high sulfur Illinois coal is available, the south-north shipment of coal within Illinois will be greatly increased but the shipment of Wyoming coal to Illinois will be purely academic.

Appendix 1

State of A Gaseous Suspension

We note that the 2-x0" coal is readily transported by a pneumatic pipeline without further preparation (Ref. 4). Coal size of 1 to 5 mm which might be produced by coal washing and other handling is actually favored in a pneumatic transport system and gasification system. Preparation, if any, for pneumatic conveying will be minor. Moreover, recent evidence from test results of the Bureau of Mines by Konchevsky et. al. (Ref. 4) shows that the pressure drop or power consumption is far below that given by Reference 1 with an accurate basis for correlation of data. For long distance shipment, our recent study has shown the feasibility of separating coal from air at each station; the air is recompressed and the coal subsequently reentrained. Because of the size of coal and its dry form, a pneumatic pipeline is compatible with the railroad and barges, either for supplying to or for distribution from these systems. The high velocity (10 times of the slurry line) and small holdup in the pipes render the system readily controlled according to the demand of coal. Rapid shipment also eliminates storage need at one end of the pneumatic pipeline.

Studies on the subject of gaseous suspensions often refer to a suspension as "dense phase" or "dilute phase". The extremes of each are obvious but a sharp division is not defined.

For the flow of a suspension of mean solid particle size d_p in a pipe of diameter D, parameters of interest are material densities of the solid and the gas $\bar{\rho}_p$ and $\bar{\rho}$, mean velocities of phases u_p and u, the density of particle cloud $\rho_p = \phi\bar{\rho}_p$, and $\rho = \bar{\rho}(1 - \phi)$ for the density of the gas in the mixture, ϕ being the volume fraction solid, we have the mass flow ratio of the phases:

$$\dot{m}^* = \rho_p u_p / \rho u \qquad (1)$$

since $u_p < u$ in general (Ref. 5), $m^* > \dot{m}^*$.

The mean interparticle spacing is given by the number density of particles n:

$$n^{-1/3}/d_p = (\pi/6\,\phi)^{1/3} \tag{2}$$

The ratio of mean free path of particle-to-particle collision (Λ) to interparticle spacing is given by:

$$\Lambda / n^{-1/3} = \phi^{-2/3} (36\pi)^{-1/3} \tag{3}$$

is a measure of the freedom of movement of particles thus giving a measure of whether the phases are dense or dilute.

For coal particles in air, $\bar{\rho}_p = 81.2$ lbm./ft^3 (sp. gr. = 1.3) at pressure P in atmospheres and temperature of 540 R (300 K), we have:

$$m^* P_{atm} = 1.104 \cdot 10^3\ \phi/(1-\phi) \tag{4}$$

Moreover, the total flow rate of solid $\dot{m}_p$ is given by:

$$\dot{m}_p/(\pi/4)D^2 u = 0.07355\ \dot{m}^* P_{atm} \tag{5}$$

which shows that the product $m^* P_{atm}$ is directly proportional to the through-flow for a given pipe diameter and flow velocity.

The relations given by Eq. (2), (3), and (4) are incorporated in Fig. 1 for various volume fraction solid ϕ, with P_{atm} from 1 to 100 atm. and m* of 10 to 10^3. Ranges of data of Konchevsky (Ref. 4), 1962 Report (Ref. 1), Dogin et. al. (Ref. 6), Hariu et. al. (Ref. 7) and Vogt (Ref. 8) are shown for the "dilute phase" studies. Also identified are the ranges of Zenz (Ref. 9), Sandy (Ref. 10), Albright (Ref. 11), and Wen et. al. (Ref. 12) for the "dense phase". Marked on the lines of Fq. (4) for constant ϕ are ϕ, interparticle spacing/particle size, $m^* P_{atm}$, and the free path/interparticle spacing in the parantheses. Since the main difference between the dilute and the dense phase suspensions is in the freedom of movement of particles, we may assume the dividing line along the line of $\Lambda/n^{-1/3} \sim 1$ or $\phi \sim 0.1$.

Fig. 1 shows that for a given state of suspension, increasing pressure will not increase the solid flow capacity. Hence there is an optimum between the atmospheric pressure or vacuum and the high pressure of thousands of psia. This is because a high gas density calls for a lower suspension velocity, a relation to be treated in a later presentation.

Also noted in Fig. 1 is the range of design study in the 1962 Report of coal dust suspension in methane. It is seen that inspite of its low mass flow ratio, because of high pressure, it actually corresponds to the most dense phase suspension ever experimented. Since $u_p < u$, the actual m* is expected to be much higher. The range of experiments on coal in the 1962 Report (Ref. 1) is also shown in Fig. 1, the actual m* is likely to have been much higher because of unsteady flow produced by the feed system.

It will be shown that the advantage of high pressure diminishes beyond 10 to 20 atm. of line pressure at $\dot{m}^*$ of 10 to 20.

Appendix 2

Friction Factor

An extensive systemmatic effort of correlating the pressure drop in pipe flow of suspensions was that of Pfeffer (Ref.13). Because of the wide scatter of data, no general correlation was possible, although some trends were noted. His study included the results of Dogin (Ref. 6), Hariu (Ref. 7), Vogt (Ref. 8) et. al. The methods will be extended to recent results in the following.

For isothermal pipe flow of a gaseous suspension in the system with pipe diameter D, length L, elevation H at one end, and total flow of solids and air $\dot{m}_p$ and $\dot{m}_a$ respectively, the pressure drop dP over a length dx is given by:

$$dP = -4\, f_m \left(\frac{dx}{D}\right)\left(\bar{\rho}\, \frac{V^2}{2g}\right) - \left(\frac{d(\rho_m V^2)}{g}\right) - \rho_m\, dh \qquad (1)$$

where f_m is the friction factor of the mixture of gas and solid, V is the gas velocity, Pm is the density of the mixture $\rho_m = \rho + \rho_p$, g is the gravitational acceleration for ρ is lbm./ft^3; dh is the rise in elevation over dx. In eq. (1), the first term on the right hand side is the pressure drop by friction, the second term for acceleration, and the third term is for gravity effect because of the elevation. Note that the mass flow G is given by

$$\rho_1 V_1 = \rho_2 V_2 = \rho V = \dot{m}_a / (\pi/4) D^2 = G \qquad (2)$$

where subscript 1 is for the inlet and 2 is for the outlet.

The friction factor of turbulent pipe flow of a simple fluid such as air in a smooth pipe is given by

$$f_a = 0.046/Re^{0.2} \qquad (3)$$

where the Reynolds number Re is given by:

$$Re = D\rho V/\mu = DG/\mu \qquad (4)$$

where μ is the viscosity of the gas.

For small change in pressure or density of the gas phase, Fq. (1) is integrated as an incompressible fluid:

$$P_1 - P_2 = 4f_m \frac{L}{D}\frac{G^2}{2\rho g} + (1 + \dot{m}^*)(\rho/g)(V_2{}^2 - V_1{}^2) + (1 + \dot{m}^*)\rho H \tag{5}$$

for small $\emptyset$, $P \sim \bar{p}$ of the gas. For large change of pressure P_1 to P_2 of the gas, the compressibility of the gas is accounted for via integration to:

$$\left(1 - \frac{P_2^2}{P_1^2}\right) = 4f_m\left(\frac{L}{D}\right)\frac{\rho_1^2 V_1^2 RT}{P_1^2 g} + (1+\dot{m}^*)\frac{2G^2RT}{g}\ln\frac{P_1}{P_2} + (1+\dot{m}^*)\frac{2\bar{P}^2 H}{RTP_1^2} \tag{6}$$

for inlet pressure P_1 and velocity V_1.

These relations were used to evaluate the data in Table IV-3 of the 1962 Report (Ref. 1) on the flow of coal, f_m obtained from them are close. Fq. (2) was used to evaluate the data of Konchevsky (Ref. 4) in straight runs of pipes because of the small change of pressure. The data of f_m/f_a vs Re are shown in Fig. 2; with ranges of $\dot{m}^*$ and pipe size indicated. Note that for similar $\dot{m}^*$ and Re, tests reported in the 1962 Report give f_m/f_a values of one to two orders of magnitude larger than those obtained from Konchevsky tests which were based on vacuum suction of coal 4-x0" coal. This comparison confirms the suggestion that because of unsteady flow m* in the 1962 report had reached much higher values than the reported averages. Konchevsky et. al. also concluded that the size of coal has insignificant effect for $d_p < (1/3)$ D. Experiments of Sproson et. al. (Ref. 24) show similar ranges as Konchevsky.

The results of Konchevsky appears to be adequately correlated by the relation proposed by Dogin and Lebedev (Ref. 6) according to:

$$f_m = f_a + A\left(\frac{d_p}{D}\right)^{0.1} Re^{0.4}\ Fr^{0.5}\ (\bar{\rho}_p/\bar{\rho})\ \dot{m}^* \tag{7}$$

where Fr is the Froude number

$$Fr = V^2 / g\ D \tag{8}$$

which accounts for the gravity effect in horizontal pipe flow. A is a

parameter depending on the roughness of the pipe. For the data of Konchevsky,

$$A \sim 2 \cdot 10^{-7} \tag{9}$$

instead of $10^{-6} < A < 2.10^{-6}$ proposed by Dogin et. al. $A = 2.10^{-6}$ seem to correlate the data on coal dust in 1962 Report (Ref. 1).

Another correlation to account for the effect of mass flow of solid and the density ratio of phases was suggested by Rose and Barnacle (Ref. 14), which can be expressed in the form:

$$f_m = f_a + (\pi/8)\, \dot{m}^* \, (\bar{\rho}_p/\bar{\rho})^{1/2} \, \psi \tag{10}$$

ψ was given as a function of Re having a value below 10^{-5} for Re $>$ 35,000 However, calculations from Konchevsky's data give $\psi \lesssim 10^{-4}$.

Pfeffer (Ref. 13) , from coding various sources of data suggested:

$$f_m = f_a \, (1 + \dot{m}^*)^{0.3} \tag{11}$$

without regard to other factors. This correlation tends to give an optimistic estimate of pressure drop and we shall treat it as the lower bound of f_m.

Extensive measurements were made on transport of pulverized coal through pipes by Patterson (Ref. 15). It was a pity that not a single set of data was taken on a straight run of pipe for comparison; records on bends were archaic. His use of gamma-ray detection of sedimentation appears useful.

Design for telescoping of pipes is illustrated in Table 3. A typical mechanical system was illustrated by Topper et. al. (Ref. 22) but optimum design remains to be made in our continuing study.

Table 3

Telescoping of pneumatic pipelines for
Long Distance Transport (1/4-x0" coal)

(13,000 tons/day, 17 atm inlet pressure, 1 atm outlet)

Standard pipe schedule 20 Nominal Dia., inches	Inside dia., ft.	Lift parameter 7.5		Lift parameter 10	
		Mass flow ratio 10	Mass flow ratio 15	Mass flow ratio 10	Mass flow ratio 15
		(following length in miles)			
8	0.625				
10	0.7917		1.745		
12	0.9583		9.15		16.38
14	1.2810	14.59	6.42		14.38
18	1.4480	16.52	5.63	26.06	11.70
20	1.6040	23.51	8.06	44.87	15.32
24	1.9380	19.98	4.40	40.10	12.57
30	2.4170	12.61	9.94		
	TOTAL:	87.21 mi.	43.36mi.	111.04mi.	70.35

Appendix 3

Breakage, Wear and Safety

A natural concern when considering the pneumatic conveyance of solids is the wear of components and the deposition of fines due to breakage of coal in the system. Note that in the first place, breakage of coal is less likely at high air pressures than at atmospheric pressure because of the higher density of the gas which results in a reduced velocity of impact of the particle on a surface. It is readily shown that at 10 atmospheres of pressure, the impact velocity of a particle for a given flow velocity and geometry is 1/3 of that at atmospheric condition. This is because the resistance to relative motion of solid particles in air is proportional to the product of the density of air and the square of relative velocity. The resulting intensity of impact will be $(1/3)^{6/5}$ or 1.4 of that at atmospheric condition (p. 208, Ref. 5). Hence, at the prevailing temperature, all wear and deposition due to fines will be reduced. Deposition will also be less due to reduced area of contact and intensity of contact. The magnitude of wear and the provision needed to reduce deposition remain to be determined via model testing. The amount of metal removed by the impact is nearly 1/9 of that at atmospheric condition (Reference 5, 24). Because of the above argument, it is postulated that cyclone wear will be less at the elevated pressures than at atmospheric pressure.

Safety

Recent work at the University of Illinois at Urbana-Champaign supported by the Bureau of Mines has shown that when coal dust suspended in air with a one-to-one mass ratio was ignited in a tube, the fines below 20 microns were ignited but the resulting flame was smothered by the coarser coal particles. Since our proposed system handles coal chips below 0.25 inch in size with a 10-to-1 coal-to-air mass ratio, it has been demonstrated

in practice that a pneumatic pipe transport system for underground coal haulage is conducive to a safer and more healthful mine than by conventional means (Ref. 4., experiments at Morgantown Energy Research Center, Bureau of Mines).

Appendix 4

Outline - Systems and Costing

1. SYSTEMS

   Rail

   Water Slurry Pipe Line

   Pneumatic Pipe Line

   Excluded: Oil Slurry

   Natural gas-coal

   Mix: Pneumatic, Rail, Barge, Mixed Material

2. BASIC PARAMETERS

   Tons/day

   Distance miles

3. COMMON STEPS - Different by Technological needs

   Mine

   - Loader
   - Breaker

   Supply Point

   - Storage
   - Preparation

   Transportation

   - Distance
   - Elevation
   - Intermediate Stations - number and type

   Receiving Point

   - Storage
   - Separation
   - Distribution

4. APPLICATIONS

Power Generation

Gasification

Basis for Comparison: Cent/Ton- miles

Environmental Impact

COSTING - (Given: Tons/Day and mile distance)

CAPITAL COST

A. Preparation Equipment

Loading facility or main pumping facility

Building, land, storage

Engineering 16%

B. Pumping or Intermediate Stations

(number = (distance/spacing) - 1)

Land, Structures

Equipment

Piping or rail, transmission lines

C. Receiving Facility

Equipment for separation and distribution

Building, Land, Storage

TOTAL CAPITAL COST: ____________________

ANNUAL COSTS

A. Fixed charges or debt

1. Total capital split: 55% debt

45% equity

2. Interest on debt = 9%

Interest on equity = 15%

Return on rate base = (0.55) (0.09) + 0.45 + 0.15 = 11.7%

ANNUAL COSTS (Continued)

A. Fixed charges or debt

3. Average rate base = total capital cost/2

4. Debt retirement - amortization period = 25 years

a. Rate base: (3) (11.7%) (Alternate 15%)

b. Federal Income Tax (28%) . (a)

c. Depreciation = Total capital cost/25

TOTAL DEBT RETIREMENT= ______________________

B. Annual cost of operating labor

1. Labor and Supervision

a. Superintendent

b. Repairmen

c. Helper

d. Shift men

2. Materials and Maintenance

a. Repair cost - $2/hp

b. Oil cost - $0.1/hp

c. Supplies - $1.5/hp

d. Total annual maintenance of structures, facilities, site and miscellaneous.

TOTAL:

C. Annual cost of administration and engineering.

Estimated (50% of B)

D. Total cost of labor, materials, administration, and engineering of each element.

E. Total cost of labor, etc. - for the system

F. Annual Fuel Cost

1. Coal required or its equivalent fuel cost

2. Oil

G. Total annual cost of owning and operating

1. Fixed charges on debt

2. Labor, material, and engineering

3. Fuel

H. Cost per ton of coal delivered

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LONG DISTANCE HIGH PRESSURE PNEUMATIC TRANSPORT SYSTEM FOR GRANULAR MATERIALS INCLUDING COAL

S. L. Soo

SYSTEM

Granular materials can potentially be transported more economically suspended in a high pressure pneumatic pipe conveying system than by railway or truck, especially when the consumption of fuel oil in locomotives or trucks needs to be curtailed. The long-range fuel situation, of course, makes a pipeline (consuming electricity from coal or nuclear energy) more attractive than ever before. By "granular materials," we mean grains, polyethylene chips, or other granular chemicals, and coal up to one inch in size. Because of drag reduction characteristics of a particulate pneumatic suspension, it often takes no more energy to pump a suspension than to pump air alone. The actual pressure drop for a given size of each type of granular material remains to be determined.

Long distance pneumatic transport was not used in the past because pneumatic conveying systems have commonly been designed to operate at below atmospheric pressure as, for example, in a vacuum cleaner. A vacuum system calls for large pipes and has a large friction loss and large power consumption and would not compete with railway transportation.

The proposed system consists of a high-pressure pneumatic transport system made possible by the concept of a cyclone-compressor-venturi module as shown in Fig. 1. Such a system provides pumping (compression) without having the bulk of the granular material passing through the compressor. The initial gathering system may be steady or intermittent in its operation. As can be seen in Fig. 1, the granular materials are removed by a cyclone and held up in the bottom cone of the cyclone while the clean air passes through the compressor. The collected

particles are then re-entrained in the venturi section located and attached to the base of the bottom cone of the cyclone and transported on to the next station. The cyclone is capable of collecting particles above 5 microns in diameter at efficiencies greater than 98 percent or better.

A possible high-pressure pipeline system, illustrated in Fig. 2, has a 12-in. diameter line at 15 atm maximum pressure (optimized design of a given application may change these parameters) and a 40 to 50 feet per second mean flow velocity, with pumping stations consisting of the cyclone-compressor-venturi module located at 20-mile spacings. The optimum parameters remain to be determined. Such a system for a 400-mile transmission is expected to handle at least 12,000 tons of solids per day and may handle as much as 25,000 tons per day. This latter condition is equivalent to about 10 percent solid void fraction. The determination of the upper limit is one of the objectives of the proposed testing. The estimated pumping power required at the starting point in the system is 8,950 hp with each station requiring 1,170 hp. There is a recovery of 1,940 hp at the turbine at the delivery end (or 3,880 hp with preheating of the air to 600°F) of the system. Hence, a total power consumption of 30,000 hp or less will be needed. This power will be produced by less than 2% of the Btu value of the coal transported (based on 40 percent generating efficiency and 70 percent compressor efficiency). The cost of shipping is anticipated to be below that for railway hauling, considering the labor saved in an automated pipeline system and the reduced loss of fines due to wind. If pneumatic transport of mining becomes practical, the coal mined will be millimeter size chips. This may make rail shipment in open cars impractical due to wind losses.

It should be noted that the temperature of the air in the pipeline will be raised approximately 150°F for the pressure rise illustrated in Figs. 1 and 2. This higher air temperature will result in a higher coal temperature which may reduce the tendency of the coal to agglomerate. This would be beneficial

for use in gasification processes because the tendency of the coal to cake would be reduced.

The feasibility of the pneumatic transport of crushed coal has been demonstrated in current development efforts conducted at the Morgantown Research Center of the U.S. Bureau of Mines. Operating with a vacuum (20 in. Hg) suction system, 18 tons of 0.25-inch mean size coal were transported through 200 feet of 6-inch diameter pipe. For 500 feet of 12-inch pipeline, the haulage rate would be 70 tons per hour. This would require 5,100 cfm of air and 145 hp [1].* Experiments were also conducted with 20 psig pressure at the coal pick-up point [2]. These results compare favorably with similar work performed in England and Germany [1,2]. The possibility of pressurized transport was also demonstrated in a study of pneumatic stowing [19]. When one compares the high pressure system with the vacuum system, it is noted that:

1. Operation at pressures of 10 atmosphere level makes spacings of 20 miles or more between pumping stations may be feasible for pipes above 12 inches in diameter. The reason for this is the desirability of maintaining a reasonable pressure loss and a low friction loss in pipe flow and the maintenance of a low mean air velocity (below 60 to 80 fps).
2. Drag reduction effects become more obvious at large flow Reynolds numbers based on pipe diameter [3].
3. Successful operation of the cyclone-compressor-venturi system requires a low ratio of the maximum and minimum pressures so that the venturi and particle feed can operate efficiently.

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*Numbers in brackets refer to entries in REFERENCES.

4. For high pressure transport, the close coupling between the particles and the air permits successful operation at large changes in elevation. This is because potential energy of the particles is effectively transferred back into kinetic energy of the mixture [4].

5. Below an upper limit of loading of solids to air, the power consumption is not significantly affected by the loading.

CONTROL AND EMERGENCY PROCEDURES

Because of the nature of a suspension, that is when the flow stops, the solids settle down, provisions must be made for: start-up, programmed stopping, stopping when a partial power outage occurs at one of the substations, complete power outage or shut-down, an emergency procedure when the line breaks, and a system for dealing with an explosion.

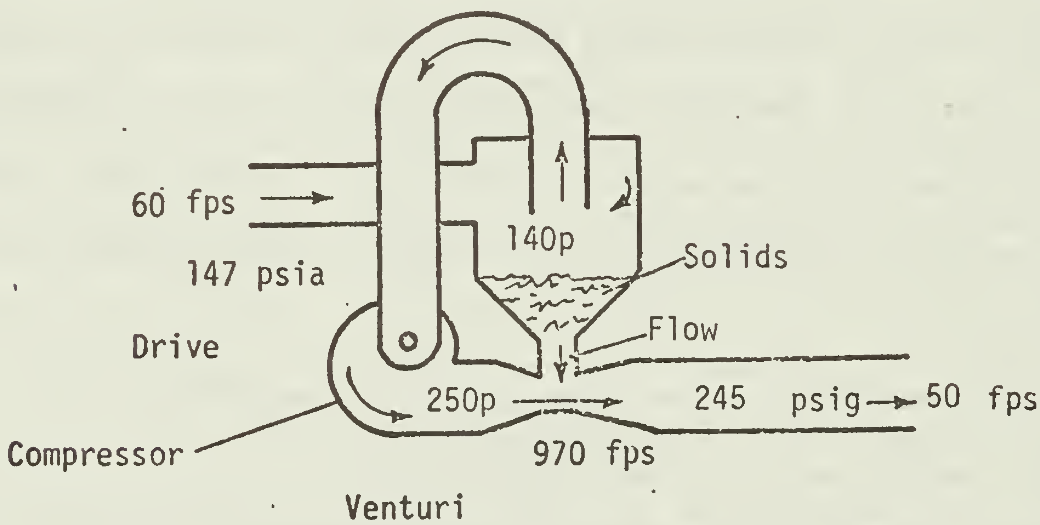


Figure 1 A Cyclone-Compressor-Venturi Module with Parameters Indicating Operating Condition of a 10-Atmosphere System

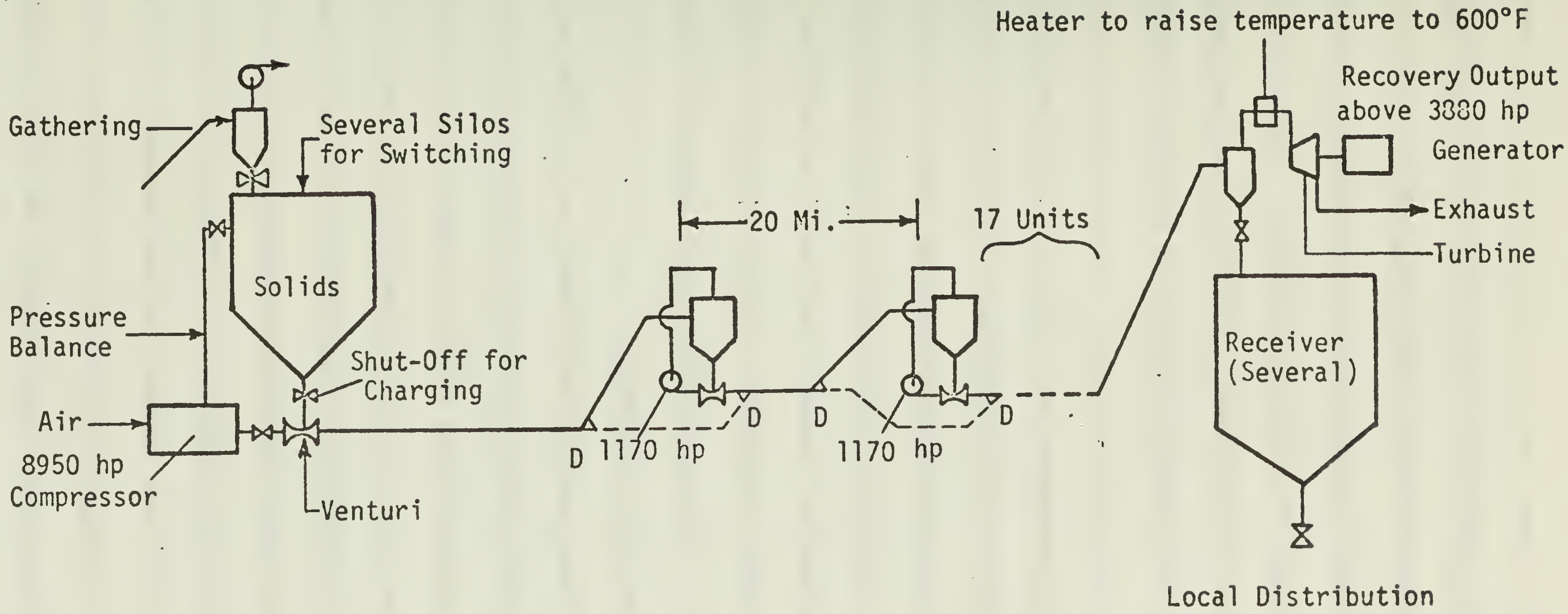


Figure 2 A Typical High-Pressure Pneumatic Pipeline System (Example of a 400-Mile System for 12,000 to 25,000 Tons of Coal per Day, D-Diverter Valves for Station By-Pass)

Start-up can be made for a clean line by building up the line pressure and flow of air by starting the compressors sequentially down the line. Once the pressure in the line is built up to the design level, solid material is introduced and the desired steady flow is established. A programmed stop is made by reversing the start-up procedure. The nature of a solid suspension is such that it is desirable to clear the pipe of solids prior to the next starting. For a 400-mile line at 60 fps flow velocity, this would take 10 hours.

For a system designed with over-pressure capacity, provision of a station by-pass through diverter valves would permit the line to continue to run at reduced capacity in the event a compressor at one of the substations breaks down. Loss of power at a few stations would necessitate a programmed stop or an instantaneous complete shut-down. A complete power outage would result in the instantaneous stopping and shutting off of the coal input to the line. This would allow the solids to settle in the pipes. Let us now consider three situations:

1. Situation A is that for a straight horizontal run of pipe, 10 to 20 percent of the flow area will be blocked by the settled solids. Inertia may carry 100 to 500 lbs of coal (amount in the stopping distance) into each downstream cyclone. This extra input must be provided for in the design to prevent plugging. Our experience shows no problem for restarting by re-entraining even with air at atmospheric conditions [6] unless excessive wetness of the coal exists. In such a case, a longer duration of running on clean air at the next start will dry up the coal. If the settled coal is only moist, the introduction of coal into the line at the next start will knock the remaining

settled coal loose. Starting after an emergency stop will be made by starting downstream stations first to ease the build-up of solids during establishing a flow of inlet air. The proposed study will examine the effect of surface moisture on coal transport.

2. A contingency situation B is when a short length of the pipe is plugged. It should be noted that at the next start on clean air, a pressure differential of 100 psia is readily built-up across such a 'plug' for a 12-inch pipe (this maounts to a pushing force on the plug of 5.7 tons or the equivalent of a 300-hp bulldozer pushing dirt with a 2 ft by 6 ft blade at 1 mph). Therefore, restarting difficulty is not expected under ordinary circumstances. Situation B may occur with a dip in the line such as when the line is to cross a river.

3. The worst situation would be Situation C when all of the coal in a 20-mile line would 'bunch' together giving a 'plug' two miles in length. This would call for clearing the line through blow-off panels (for risk control). The location of the plug could readily be found from pressure taps measured along the line at the next start. The plug would first be punctured with a drill and the line cleared by gradually building up pressure with clean air. Situation C occurs when the solid outlet of one of the cyclones is plugged. Situation C is avoided by actuating to open diverter valves [11] with solid level sensors in a cyclone or a mass flow sensor downstream which shut down the line when the situation does not correct itself and when the through flow cannot be maintained. Note that at 10 percent volume fraction solid, a 20-mile length of 12-inch diameter pipe holds 340 tons of coal.

When a line breaks at a point, a complete shut-down has to be made. Leakage in the length between two stations may reach 90 percent hence station spacing

has to be limited because of this possibility as well as others. Yet coal leakage can be limited in the station area with a suitable enclosure. This system is, in a way, a desirable characteristic because the coal remaining in the line will be minimal which will facilitate the repair.

When safety is considered in a later section, it will be shown that an explosion in a high pressure line is less likely than in one at atmospheric pressure. In order to examine the worst possible case, let us consider the consequence of an explosion and how it might be controlled. When a sensor (optical or ionizing sensor) detects a flame front, an electrical signal will trigger a mechanism controlling the dump gates at both sides of the flame front and shut-down the whole system. The result is not too different from a line break due to failure of material. Based on our experience and our design calculations, both of these conditions are unlikely.

COMPARISON TO OTHER SYSTEMS

In comparison with natural gas transmission pipelines, oil pipelines, and coal-water slurries, the high-pressure transmission of coal in suspension is more desirable since it is a compact form of energy comparable to oil; however, coal-air suspension flows more like a gas. Specific data are presented in Table 1. The uncertainty of the maximum amount of coal that can be conveyed shows the need for testing on a high pressure suspension. In Table 1, it can be seen that even for coal gasification, it might be more desirable to transport coal by an air suspension at high pressure to the most convenient point for the processing. The need for water and for the utilization of the energy released is thus more conveniently handled.

Another form of coal transfer using a pipeline is in a water slurry. The air suspension at high pressure is more desirable because of the following features:

Table 1 Comparison of High-Pressure Transmission of Coal in Air Suspension with other Systems*

Form	Gas	Oil	Coal (Air Suspension)	Coal*** (Water Suspension)
Heating Value	1,000 Btu/ft^3	18,500 Btu/lb	12,000 Btu/lb	12,000 Btu/lb
Flow	240 mmscfd**	37,000 bbl/day	10,000 tons/day may convey up to 20,000 tons/day****	10,000 tons/day
Line Pressure, psig	68 atm		15 atm	68 atm (heavy pipe costs more)
Energy Density, Btu/ft^3	6.8×10^4	9.68×10^5	7×10^4 (to 1.4×10^5)	5×10^5
Practical Flow Velocity, fps	30 to 60	5 to 10	40 to 60 ft/sec	8 ft/sec
Pipe Diameter, inches	16 to 12	10 to 7	12 inches	11 inches
Power Requirement, hp	25,300	26,850	24,450	20,240
Volume Fraction Solid			4.5% (to 9.1%)	32.4% (particles nearly one 'diameter' apart--greater danger of clogging) Volume fraction solid

*Based on an equivalent 10^{10} Btu/hr transmitted.

**Million standard cubic feet per day.

***Converted from Black Mesa Pipeline data.

****This is for comparison. Figure 2 showed 12,000 tons per day. This means the desirability of large transport tonnage.

1. The air suspension is non-freezing.

2. There is less chance of clogging because air suspension works in the state of low density of suspension at high velocity (10 times in the air system).

3. There is no water pollution in the air syste. There are several strategies for removing or utilizing fines at the end of the pipeline.

4. The air system handles dry material. The transmission system can transfer soluble solids and eliminates the cost of drying and its consequent energy consumption.

Coal suspensions are chosen for the flow medium in this modeling study as well as plant study because of coal's important place in the overall energy picture.

The availability of a pipeline for the economical shipment of coal means flexible siting of coal burning power plants and gasification and liquefaction facilities from the point of view of the availability of water and utilization of heat released in processing. This is also true for transporting shale to central retort facilities. In comparison to diesel fuel powered unit trains, not only is there a savings in energy consumption (one half) but there is also a savings in diesal fuel, a reduction of labor costs, and the elimination of wind loss of coal from moving railway cars.

Based on facts reported by Risser [9] which include:

> "... 7 million tons of Wyoming coal per year, hauled approximately 1,200 miles from mine to utility plants...about 750,000 barrels (railroad diese fuel) per year, equivalent to about 3 to 5% of the heat value of the coal being transported...",

it can be shown that the energy for transport is approximately 450 Btu/ton-mile However, the loss of coal fines during shipment may be as high as 5 percent.

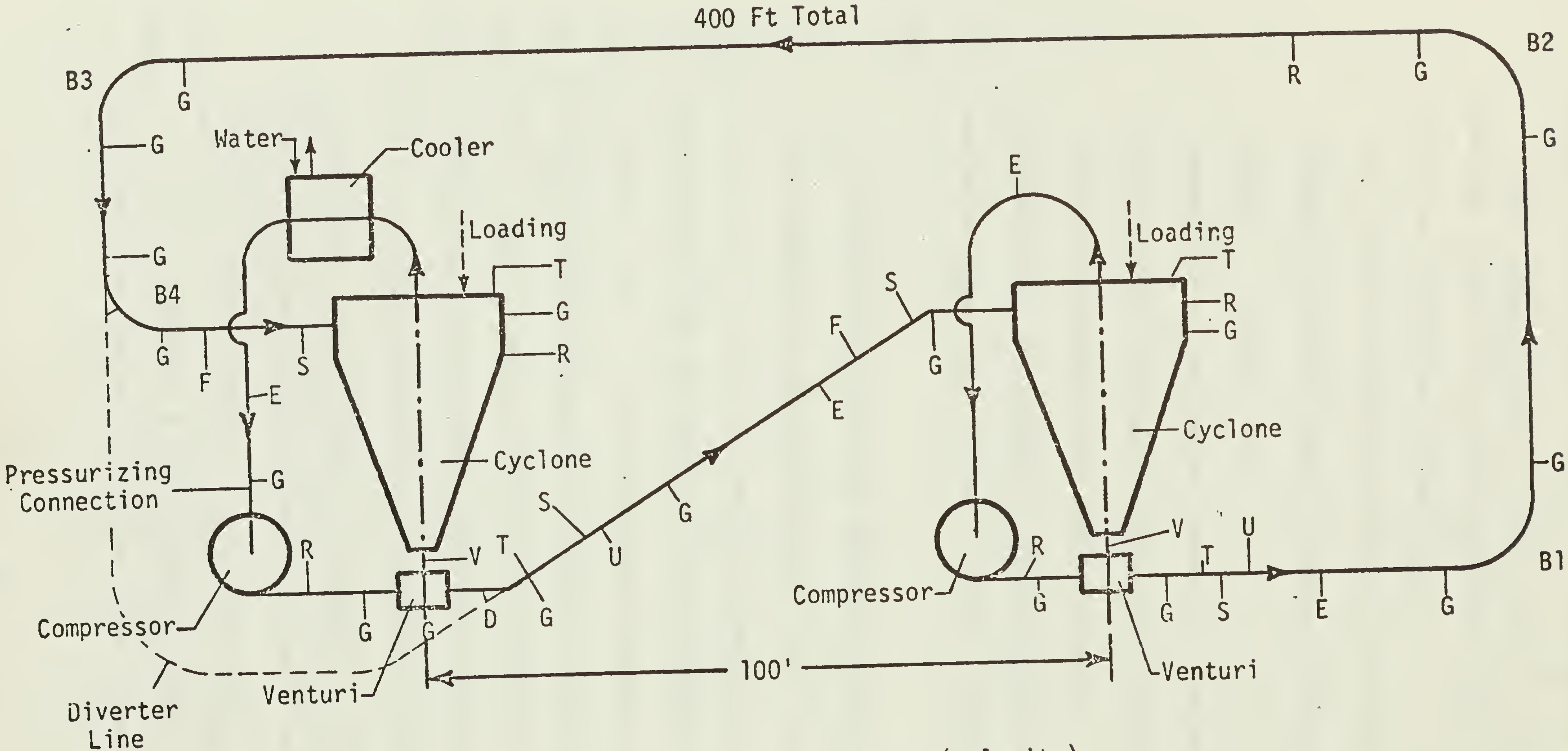
e energy loss associated with the loss of fines during transport in the above require that the energy 'utilization' factor during transit raised to 1,450 Btu/ton-mile. The main point is that the unit train nsumes diesel oil while the pipeline can be driven by electricity generated coal. Conservative estimates of the energy requirements for transporting l at rates ranging from 10,000 tons per day up to 25,000 tons per day a 12-inch high pressure line over a 400-mile stretch utilizing 24,450 range from 940 Btu per ton-mile down to 370 Btu per ton-mile. Compar- the 450 to 1,450 Btu per ton-mile of energy needed for the unit train h the projected 370 to 940 Btu per ton-mile for the pipeline, it is esti- ed that the energy needs of the pipeline system will be below that of unit train. To illustrate the influence of various design parameters, 0-inch diameter line pumping at a 10^5 tons per day level would lower the e to 330 Btu per ton-mile.

However, a preliminary analysis will show that the fuel energy con- ption is a small factor in the unit cost of transport, but replacement diesel fuel consumption is a desirable feature.

The loss of fines during shipment by rail will become more of a problem the future because of current mining techniques:

1. Automation of mining which would utilize a pneumatic system [1] would require mined coal size to be below one inch in size.
2. Coal benefaction at the mine by washing [10] may require the re- duction of the coal size for shipment to 0.25-inch level.

In regard to point 2 (above), it should be noted that coal benefaction the mine is also desirable as a way of concentrating the energy density u/ton). By way of example, if the ash content is reduced from 20 percent 10 percent while the total sulfur is reduced from 5 percent to 2.5 cent of total weight, the heating value would be increased by approximately percent.



E Electrostatic Probe (mass flow)
F Fiber Optics Ti Diode
G Gauge, Pressure
R Rupture Disk
T Transducer
D Diverter Valve
S Shapiro Probe (velocity)
U UV Pressure (Piezoelectric)
V Shut-Off Valve and Discharge
B1, B2, B3, B4 Bends of Various Radii

Figure 3 Test Loop for Pipeline Modeling

Loss of coal during shipping by rail and dumping could then reach unacceptable levels. A pipeline, however, fits in with the handling procedure of the above steps of mining and benefaction.

The coal pipeline or multi-purpose pipeline for granular materials are, in effect, conversion devices of coal-to-oil via replacing the oil needed in railway and truck shipment with coal generated electricity.

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LONG DISTANCE HIGH PRESSURE PNEUMATIC TRANSPORT SYSTEM FOR GRANULAR MATERIALS INCLUDING COAL

(June 1, 1974)

S. L. Soo

This addendum was prepared as a result of discussions with members of the engineering staffs of the Illinois Power Company and the Commonwealth Edison Company. In particular, the addendum addresses itself to further details in the following areas: safety, erosion, corrosion and alternate approach, costs, and cooperation with industry. Because of its simplicity and flexibility of design, a pneumatic pipeline may be applied to complement and supplement an existing rail system.

Safety

Recent work of Professor R. A. Strehlow at the University of Illinois at Urbana-Champaign supported by the Bureau of Mines has shown that when coal dust suspended in air with a one-to-one mass ratio was ignited in a tube, the fines below 20 microns were ignited but the resulting flame was smothered by the coarser coal particles. Since our proposed system handles coal chips below 0.25 inch in diameter with a 10-to-1 coal-to-air mass ratio, Professor Strehlow's experiments give evidence to reinforce our statement regarding the safety of the proposed system. It has been demonstrated in practice that a pneumatic pipe transport system for underground coal haulage is conducive to a safer

and more healthful mine than by conventional means (Ref. 2, p. 21 of proposal, experiments at Morgantown Energy Research Center, Bureau of Mines). The alternative approach of using deoxygenated air would make any explosion hazard even more remote. In any case, the absolute operational safety of the proposed system is to be demonstrated by the laboratory experiments.

Erosion of Machinery by Fine Dust

A concern regarding erosion of the inlet of the compressor rotor blades calls for some clarification. This is in view of the fact that a coal burning gas turbine project was abandoned by the Bituminous Research in the 1950's because of the severe erosion problem of the turbine blades by fine ash (microns in size). The problem was that blade strength consideration at high temperatures (say, 1,200°F) led to the design practice of high flow velocity for short turbine blades; this gave a high impact velocity of dry dust and severe wear especially because of reduced surface strength at such high temperatures. In the present case of centrifugal compressors for the high pressure pneumatic pipeline, the situation is quite different. The fines of the coal dust below 10 micron at 80°F retains adsorbed moisture, making it less abrasive than when it is dry, and the flow velocity relative to the blades at the compressor inlet is less than 1/10th of that in the above turbine. Therefore, blade erosion problem, if any, will be less than 1/100th of that in a coal burning gas turbine with similar dust control by cyclone separators over the same period of time.

Corrosions and Alternate Scheme

The need to ground the pipeline at various points along the path has raised concern regarding the possibility of corrosion due to the cell action expected in the presence of moisture in the ground. Design for anodic protection might be needed. This problem, of course, will be addressed in the proposed investigation. An alternate approach, however, is proposed below which calls for only limited extent of grounding of the pipes.

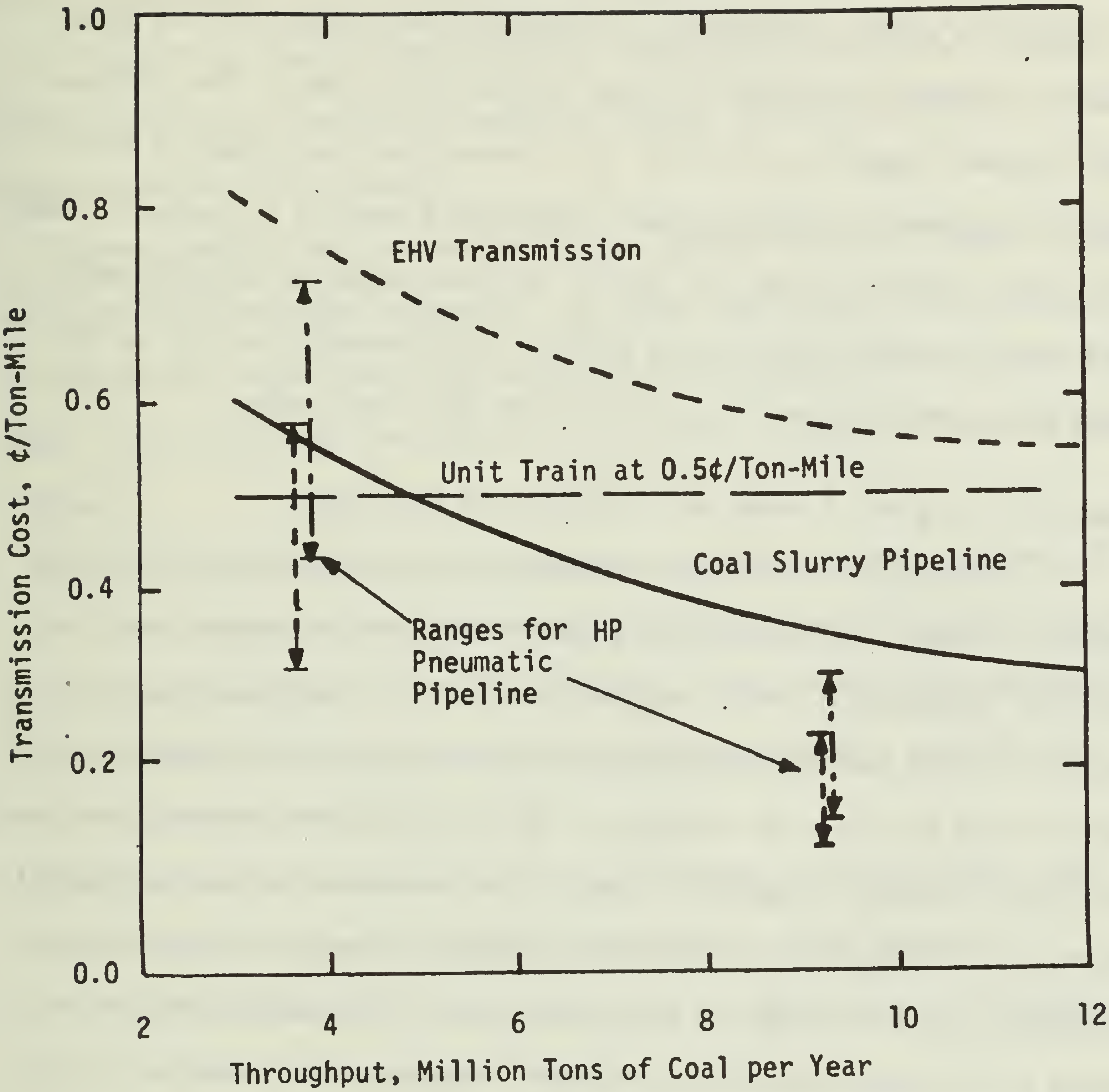
This alternate procedure would be to remove the oxygen by combustion from the carrier gas prior to injection into the pipeline. Because the oxygen necessary for an ignition will not be present in the carrier gas, any explosion hazard due to an accidental spark is removed. Note that the pipeline coal suspension is made up of one lb of air for every 10 lbs of coal. To remove this oxygen from the air, one lb of air needs to be burned with less than 1/10 lb of coal. Therefore, the removal of oxygen in the transportation air requires less than 1 percent of the coal being transported. When transporting 25,000 tons of coal per day, 300 to 350 lbs of coal per minute will be sufficient to remove the oxygen from the 47,000 cfm of air via the combustion process. Given the heat release of 3.6×10^6 Btu/min associated with this combustion, the cooling of the resulting deoxygenated gas by generating steam is equivalent to a power generation of 26,500 kw. This steam could also be used for coal drying (enough for removing 12 percent of the moisture) or combining the latter with power generation to supply a portion of the pumping power of the pipeline. The power generated could also be used for coal crushing or other preparation devices. The added investment associated with this

alternate scheme is estimated to be $7,000,000 which is small in comparison to the cost of the miles of pipeline. Savings through the elimination of corrosion and hazard prevention components are expected to reduce the net figure.

The utilization of deoxygenated air (after removing SO_2 to prevent corrosion) gives a gaseous mixture of CO, CO_2, and N_2 for transport. The pumping characteristics will be essentially the same as air. Grounding of charge generated by contact of coal particles with pipe walls will still be needed for the protection of personnel at above ground points with anodic protection against corrosion. The gain via such a system is that other pipe materials and a coating may be used. Moreover, charge generation can be controlled by the presence of moisture in the gas. At the level of 10 atmospheres of operating pressure, pipeline burst will never occur even though energy density is similar to that of natural gas at 1,000 psi (line burst had occured in natural gas pipelines). Preventive measures for pipeline burst and spillage will not be needed.

Cost of Transporting Coal

With the additional input from members of the Commonwealth Edison Company, the budget is further revised to an even more realistic level than before. This is given in APPENDIX AA of this addendum. The cost of deoxygenating the air for transport is also included. The actual increase in unit cost is expected to be lower than as shown in that savings is expected because hazard prevention devices will not be necessary with deoxygenated air. The hypothetical shipping distance is still 400 miles. Further details of cost comparison in addition to APPENDIX B is given in Fig. 4 for various throughputs over 400 miles. A shorter distance will



(EHV denotes Extra High Voltage)

All curves due to Thompson and Wasp (December 1968)

|← - - - →| denotes range for HP pneumatic pipeline (1974) based on Illinois Power Co. estimate of charge on debt

|← · — · →| denotes range for HP pneumatic pipeline (1974) based on Commonwealth Edison Co. rate

Upper limit is for buried pipe with deoxygenated air, lower limit for unburied pipe with air

Figure 4 Comparison to Transmission Costs of other Systems (Based on a Distance of 400 Miles)

shift the data in favor of smaller throughputs.

Figure 4 shows a comparison of transport coal (1974) of the high pressure pneumatic pipeline to other systems (1968 cost). The Illinois Power Company suggested a rate of 11.7 percent for the charge on debt, and the Commonwealth Edison Company suggested a rate of 15 percent. However, this difference does not affect the cost estimates significantly. The ranges as shown cover buried pipeline with deoxygenated air as the upper range and unburied line with air for the lower range.

Comparison to other Systems and Relations to Railroad

The advantage of low mixture density and high velocity of the high pressure pneumatic pipeline over a slurry pipeline is further seen considering transmission over a mountainous terrain. For going up an elevation of 1,300 feet, the hydrostatic pressure due to the mixture of coal and air will be 74 psi as compared to 850 psi in a 50-50 water slurry system. For similar energy throughput, because the flow velocity in the pneumatic system is 10 times that of the slurry system, the holdup in the pneumatic pipeline is 1/10 as large as the slurry line. This renders the pneumatic system more readily controlled as demand changes at the point of consumption. Besides, its lack of the need for the elaborate slurry preparation and separation equipment makes the pneumatic system suitable for transporting coal over short (e.g., a few miles or less) and intermediate distances (e.g., less than 100 miles) as well as long distance transmission.

Another point of comparison is that when supplying a gasification facility, the slurry pumping calls for all particles of coal to be below 20 mesh, yet gasification process such as the Lurgi cannot use a material of this fine mesh. The pneumatic system, however, because of separation

before compression, can handle particles around 0.25 inch in size.

It has been suggested that another important application to be developed is in the transport of shale to retort facilities and for subsequent disposal of tailings.

Some questions were raised as to the comparison of pipelines to railway unit train and belt conveyors. It seems that there is some general reluctance for anyone to estimate the cost of building a mile of new railroad. Two comparisons are, however, indicative of the high cost of new railways:

1. The 273-mile Black Mesa Pipeline was built because its cost is so favorable when compared to building an additional 150 miles of railroad needed by the unit train. Even on existing railroads, unit trains are operated at a higher cost than a slurry line would be (Fig. 4).
2. In another instance, a 3.5-mile conveyor belt was deemed more economical than a railroad. Note that a belt conveyor cost over $1 million per mile even back in 1962 while its operating cost was 4.5 cents per ton-mile.

Slurry preparation and separation and the resulting nature of the coal being handled in a slurry pipeline exclude further shipment of slurried coal by rail. However, because the high pressure pneumatic pipeline handles dry coal chips around 0.25-inch in size, a pneumatic pipeline can be designed to serve an existing railroad system to improve its economy and capacity, even when savings of railroad diesel fuel is not an important factor. This is a desirable option because of the importance of continued use and upgrading of the railroad to the national transportation system, in spite of the fact that the cost of building a new railroad appears prohibitive.

The pneumatic pipeline may be applied to complement and supplement the rail system and unit trains because it can be designed for shipping granular materials over a long (hundreds of miles) or a short (a few miles) distance. For short distances, small shipments in small pipes become more economical than as shown in Fig. 4 which is based on a 400-mile distance. Therefore, the pneumatic pipeline can be developed to assist an existing rail system in shipping granular materials including coal in the following ways:

1. To replace unprofitable branch lines for delivery of bulk materials to a loading terminal for rail shipment,
2. To gather from several mines to a rail loading terminal,
3. To transfer between barges and a rail terminal,
4. To distribute to several consumers from a rail terminal, and
5. To gather from several terminals to supply a large gasification facility.

The last feature may be considered as being timely in that a gasification facility has to be sited away from population centers and near a large supply of water to be used as a reactant and as a coolant and the waterway might not be in the right direction for barge shipment of coal.

For example, an interesting alternative to the 273-mile Black Mesa Coal Slurry Line in Arizona (a great engineering achievement) appears to be the combination of a 120-mile pneumatic pipeline from Black Mesa to Winona, by unit train (covered) from Winona to Kingman (220 miles) via Santa Fe Railroad, and from Kingman by a 30-mile pneumatic line to Mohave. In this case, the branches of the pneumatic pipelines are all downhill and can be unburied and no more storage capacity than the slurry line would be needed. Economical operation is expected although the overall economical detail remains to be analyzed.

APPENDIX AA

Revised Economic Estimate (May 29, 1974) with Charge on Debt with Debt Charge Rates suggested by Illinois Power Company and Commonwealth Edison Co.

CAPITAL COSTS

A. Investment/Station

1. Station

1.1 Land and Improvements

1.1.1 25 acre site @ $1,000/acre	$25,000	
1.1.2 Building roadway	$20,000	
		$45,000

1.2 Structures

Main compressor bldg. + incidental auxiliaries, e.g., cranes	$ 35,000

1.3 Equipment

1.3.1 Motor-compressor set (1170 hp) including switch Gear	$150,000	
1.3.2 Piping (in station)	$ 25,000	
1.3.3 Cyclone and venturi	$ 12,000	
		$187,000
		$267,000
Add 16% for engineering and contingencies		42,720
Total investment/station		$309,720

B. Total Station Costs

Assume: Main station at pipeline inlet = 4 substations

Main station at pipeline exit = 4 substations

Substations at 20 mi. spacing =19 substations

Total station costs = $27 \times 3.0972 \times 10^5 = \$8.4 \times 10^6$

C. Piping and Installation Cost of 400 mile pipeline (10" diam.)

Assume: $135,700/mi for buried 10" pipeline*

$67,850/mi for unburied 10" pipeline

*Based on the actual cost of a 4-5 mile buried pipeline in the St. Louis, Mo. area (1973)

Total piping and installation cost (buried) = $\$54.3 \times 10^6$

Total piping and installation cost (unburied) = $\$27.1 \times 10^6$

D. Installation of Transmission Lines to each Substation

Assume: \$0.24/ftover 400 mi. = \$500,000

E. Total Capital Investment

	Buried	Unburied
Total station cost	$\$8.4 \times 10^6$	$\$8.4 \times 10^6$
Piping and Installation	54.3×10^6	27.1×10^6
Transmission lines (installed)	$.5 \times 10^6$	$.5 \times 10^6$
	$\$63.2 \times 10^6$	$\$36.0 \times 10^6$

ANNUAL COSTS

A. Annual Fixed Charge on Debt (10" pipe)*

1. Buried pipe 10" pipe assumptions

1.1 Total Capital Split 55% debt = 34.8×10^6

45% equity = 28.4×10^6

1.2 Interest on debt = 9%

Interest on equity = 15%

Return on rate base = (0.55)(.09) + (0.45)(.15) = 0.117 = 11.7%

1.3 Average rate base = $\frac{\$63.2 \times 10^6}{2} = \$31.6 \times 10^6$

1.4 Debt Retirement - Amortization period = 25 years

Rate base = 3.70×10^6

Anticipated Fed. Inc. Tax(28%) 1.04×10^6

Depreciation = 2.53×10^6

Debt retirement buried pipe = $\$7.27 \times 10^6$

*Section A calculations based on the American Gas Assn. General Accounting Committee Procedures

Unburied Pipe 10" pipe

Same assumptions as above

Debt retirement unburied pipe = $\$3.64 \times 10^6$

B. Annual Cost of Operating Labor (accommodates 5 substations)

1. Labor and Station Supervision

1.1	1 - Station superintendent	$20,000	
1.2	1 - repairman	15,000	
1.3	1 - helper	10,000	
1.4	3 - shiftman	30,000	
			$ 75,000

2. Material and Maintenance Costs (for 5 substations)

2.1 Repair Costs $2/hp.

2.2 Oil Costs $0.1/hp.

2.3 Station Supplies $1.5/hp.

Total = $3.6/hp x 5850 hp — $ 21,060

2.4 Annual Maintenance of structures

Piping, site and misc. — $ 20,000

Annual Cost for 5 Substations (1 + 2) — $116,060

C. Annual Cost of Administration and Engineering (for 5 substations)

Estimated @ 50% of Cost of B above

Annual Cost — $58,030

D. Total Annual Cost of Labor, Materials, Adm. and Eng. for 5 substations

$174,090

E. Total Cost of Labor, Material, Adm. and Engineering

Equivalent to five times Item D: — $870,450

F. Annual Fuel Cost

1. Coal required to run motors for compressor.

Assume: 40% conversion efficiency in power plant

100% electrical trans. efficiency to substation

Coal required = 58060 ton coal/yr.

Assume: coal cost \$5/ton

Fuel cost = \$290,300

G. Total Annual Cost of Owning and Operating Pipeline (10")

	Buried	Unburied
1. Fixed charge on debt =	$\$7.27 \times 10^6$	$\$3.64 \times 10^6$
2. Labor, materials, adm. and eng.=	0.87×10^6	0.87×10^6
3. Fuel =	0.29×10^6	0.29×10^6
	$\$8.43 \times 10^6$	$\$4.80 \times 10^6$

H. Cost per Ton of Coal Delivered (10" pipe)

Assume: 10,000 tons coal/day = 3.65×10^6 tons/yr.

Buried Pipeline

$$\frac{8.43 \times 10^6}{3.65 \times 10^6} = \$2.31\ /\text{ton}\left(\frac{5.8\ \text{mil}}{\text{ton-mi}}\right)$$

Unburied Pipeline

$$\frac{4.80 \times 10^6}{3.65 \times 10^6} = \$1.32/\text{ton}\left(\frac{3.3\ \text{mil}}{\text{ton-mi}}\right.$$

Assume: 25,000 tons coal/day = 9.125×10^6 tons/yr.

Buried Pipeline

$$\frac{8,43 \times 10^6}{9.125 \times 10^6} = \$0.92/\text{ton}\left(\frac{2.3\ \text{mil}}{\text{ton-mi}}\right)$$

Unburied Pipeline

$$\frac{4.80 \times 10^6}{9.125 \times 10^6} = \$0.53/\text{ton}\left(\frac{1.3\ \text{mil}}{\text{ton-mi}}\right.$$

With $\$7 \times 10^6$ Deoxygenation Capital Cost at 11.7% Return on Rate Base

E. Total Capital Investment (add $\$7 \times 10^6$ to Item E, p. A10)

Buried	Unburied
70.2×10^6	43.0×10^6

ANNUAL COSTS:

A-1

Total Capital Split 55% debt = 38.6×10^6

45% equity = 31.6×10^6

A-3 Average Rate Base = $70.2 \times 10^6/2 = 35.1 \times 10^6$

A-4 Debt Retirement-Amortization Period = 25 years

Rate Base =	4.09×10^6
Federal Income Tax =	1.12×10^6
Depreciation =	2.80×10^6
	$\$8.01 \times 10^6$

G. Total Annual Cost of Owning and Operating Pipeline (10 in. Pipe)

	Buried	Unburied
1. Fixed Charge on Debt	8.01×10^6	4.01×10^6
2. Labor, Materials, etc.	0.87×10^6	0.87×10^6
3. Fuel	0.29×10^6	0.29×10^6
	$\$9.17 \times 10^6$	$\$5.17 \times 10^6$

H. Cost per Ton of Coal Delivered (10 in. Pipe)

10,000 Tons Coal per Day

Buried Pipeline

$$\frac{\$9.17 \times 10^6}{3.65 \times 10^6} = \frac{\$2.51}{\text{ton}} \left(\frac{6.3 \text{ mil}}{\text{ton-mile}}\right)$$

Unburied Pipeline

$$\frac{5.17 \times 10^6}{3.65 \times 10^6} = \frac{\$1.42}{\text{ton}} \left(\frac{3.5 \text{ mil}}{\text{ton-mile}}\right)$$

25,000 Tons Coal per Day

$$\frac{\$9.17 \times 10^6}{9.125 \times 10^6} = \frac{\$1.00}{\text{ton}} \left(\frac{2.5 \text{ mil}}{\text{ton-mile}}\right)$$

$$\frac{5.17 \times 10^6}{9.125 \times 10^6} = \frac{\$0.57}{\text{ton}} \left(\frac{1.4 \text{ mil}}{\text{ton-mile}}\right)$$

COST ESTIMATE BASED ON 15 PERCENT RETURN ON RATE BASE

With $7 x 10^6 Deoxygenation Capital Cost

E. Total Capital Investment

	Buried	Unburied
Total Station Cost	8.4 x 10^6	8.4 x 10^6
Piping & Installation	54.3 x 10^6	27.1 x 10^6
Deoxygenation System	7.0 x 10^6	7.0 x 10^6
Transmission Lines (Installed)	0.5 x 10^6	0.5 x 10^6
	$70.2 x 10^6	$43.0 x 10^6

ANNUAL COSTS

A. Annual Fixed Charge on Debt (10-in. Buried Pipe)

1. Total Capital Split, 55% debt = 38.6 x 10^6

   45% equity = 31.6 x 10^6

2. Interest on Debt = 11%

   Interest on Equity = 20%

   Return on Rate Base = (0.55)(0.11) + (0.45)(0.20) = 0.15 = 15%

3. Average Rate Base = 70.2 x 10^6/2 = 35.1 x 10^6

4. Debt Retirement-Amortization Period = 25 years

Rate Base =	5.27 x 10^6
Federal Income Tax (28%) =	1.47 x 10^6
Depreciation =	2.81 x 10^6
	$9.55 x 10^6

G. Total Annual Cost of Owning and Operating Pipeline (10-in Pipe)

	Buried	Unburied
1. Fixed Charge or Debt	$9.55 x 10^6	$4.78 x 10^6
2. Labor, Materials, Etc.	0.87 x 10^6	0.87 x 10^6
3. Fuel	0.29 x 10^6	0.29 x 10^6
	$10.71 x 10^6	$5.94 x 10^6

H. Cost per Ton of Coal Delivered (10-in. Pipe)

10,000 Tons Coal per Day

Buried Pipeline

$$\frac{10.71 \times 10^6}{3.65 \times 10^6} = \frac{\$2.93}{\text{ton}} \left(\frac{7.3 \text{ mil}}{\text{ton-mile}}\right)$$

Unburied Pipeline

$$\frac{5.94 \times 10^6}{3.65 \times 10^6} = \frac{\$1.63}{\text{ton}} \left(\frac{4.1 \text{ mil}}{\text{ton-mile}}\right)$$

25,000 Tons Coal per Day

$$\frac{10.71 \times 10^6}{9.125 \times 10^6} = \frac{\$1.17}{\text{ton}} \left(\frac{2.93 \text{ mil}}{\text{ton-mile}}\right)$$

$$\frac{5.94 \times 10^6}{9.125 \times 10^6} = \frac{\$0.65}{\text{ton}} \left(\frac{1.6 \text{ mil}}{\text{ton-mile}}\right)$$

APPENDIX B

Cost Comparison with Other Means of Coal Transport

For comparison to other means of coal transportation, we have the following equivalence:

\$1/ton-400 miles is nearly 10¢/10^6 Btu-10^3 mile for 12,000 Btu/lb

and

1¢/ton-mile is nearly 42¢/10^6 Btu-10^3 mile.

Take the range of \$0.53 to 2.93 per ton over 400 miles of the high pressure pneumatic transport system: In 1974 we get 0.13 to 0.73 cent per ton-mile.

A previous comparison of costs of coal transport was given by R. C. Hughes in 1969 (R. C. Hughes, Williams Bros. Co., at The 72nd National Western Mining Conference, Denver, Colorado, Jan. 30, 1969) which we quote as follows:

Carrier	Range ¢/ton-mile	Comments
Petroleum of Products Pipeline	0.2 to 0.5	No Loading or Unloading Charges
Water Carrier	0.2 to 0.5	No Loading or Unloading Charges
Slurry Pipeline	0.3 to 0.5	No Preparation or Separation Charges
Slurry Pipeline	0.7 to 1.1	Preparation and Separation Included
Railroad	0.9 to 1.4	Standard Rate; No Loading or Unloading Charges Included
Railroad	0.4 to 0.9	Unit Train Rate; No Loading or Unloading Charges Included
Truck	5.0 to 8.0	One-Way Haul; No Return Load
HP Pneumatic (1974)	0.2 to 0.8	No Preparation Charge Included; Separation Charge Included

DIFFUSIVITY OF SPHERICAL PARTICLES IN DILUTE SUSPENSIONS †

S. L. Soo
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801

ABSTRACT

The diffusivity of particles is correlated to that of the suspending fluid for various ranges of a particle-fluid interacting parameter.

The diffusivity of particles in a flowing suspension affects the distribution of density and velocity of particles and various transport processes between the phases [1].* For a dilute suspension in which the fluid motion is unaffected by the presence of particles, the particle diffusivity D_p is that arising from particle-fluid interaction only for diffusivity D of the fluid. There is not an abundance of experimental data of D, and estimation of the latter for a given physical system is not easily made. The previous relation of D_p to the nature of particle fluid interactions is reconsidered in light of recent findings.

Take the case of a spherical particle of radius a and of material density $\bar{\rho}_p$ in a turbulent fluid of intensity $\langle v^2\rangle^{1/2}$ of random velocity v and Lagrangian microscale λ: Several studies [1,2] treated the particle as a randomly excited oscillator to give, in the absence of other field forces, the particle intensity $\langle v_p^2\rangle^{1/2}$ of its random velocity v_p in the form:

$$\langle v_p^2\rangle / \langle v^2\rangle = (\pi)^{1/2} K^{-1} \exp (K^{-2}) \operatorname{erf} (K^{-1}) \tag{1}$$

where K is a particle-fluid interacting parameter given by the ratio of the response time of momentum of a particle to the time in which a fluid

*Numbers in brackets refer to entries in REFERENCES.

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element remains in a region of correlated velocity, or $K = 2 \langle v^2 \rangle^{1/2}/\lambda F$; $F = 9\bar{\mu}/2a^2 \bar{\rho}_p[1 + (\bar{\rho}/2 \bar{\rho}_p)$ where F is the inverse of relaxation time of momentum transfer between particle and fluid; and $\bar{\mu}, \bar{\rho}$ are the viscosity and the density of the material constituting the fluid phase. The assumptions leading to Eq. (1) include small relative motion between the phases giving $D_p/D = 1$ as a result [1,2]. Derivation of Eq. (1) also gives an intensity of relative motion $\langle (\Delta v)^2 \rangle^{1/2}$ between the phases, and $\langle (\Delta v)^2 \rangle = \langle v^2 \rangle - \langle v_p^2 \rangle$. This lead to a particle-fluid interaction length [3] $L_p = \langle (\Delta v)^2 \rangle^{1/2}/F$, by analogy to the kinetic mean free path, and for flow in a pipe of radius R, we get [4]:

$$D_p = \langle v_p^2 \rangle^{1/2} R \tag{2}$$

for $L_p > R$. The relation in Eq. (2) has been verified from correlating experimental results of the density distribution in a suspension of large particles in small pipes [3].

For a more general situation of a free particle in a fluid with negligible wall effect, it is readily seen that for a very small particle, or $K \to 0$, $D_p/D \to 1$. Deviation from this limiting condition is seen in that the mean squared displacement $\langle X^2 \rangle$ over a given time:

$$\langle X_p^2 \rangle = \langle X_f^2 \rangle - \langle X_{fp}^2 \rangle \tag{3}$$

where subscripts p and f denote displacements relative to a stationary observer and pf of that of particle relative to fluid because of its inertia. Hence, for $D \simeq [(\pi^{1/2})/2] \langle v^2 \rangle^{1/2} \lambda$ [1], and $D_{fp} \simeq \langle (\Delta v)^2 \rangle^{1/2} L_p$, we get

$$D_p/D \simeq 1 - [\langle (\Delta v)^2 \rangle / F \langle v^2 \rangle^{1/2} \lambda] = 1 - [1 - (\langle v_p^2 \rangle / \langle v^2 \rangle)](K/\pi^{1/2})$$

$$\simeq 1 - (K^3/2(\pi)^{1/2}) + [O(K^5)] \tag{4}$$

since Eq. (1) gives, as $K \to 0$, $\langle v_p^2 \rangle / \langle v^2 \rangle \simeq 1 - (K^2/2) + [O(K^4)]$.

For a large particle or a large value of K, large relative motion of a particle to the fluid has to be recognized; however, we still have $\langle v_p^2 \rangle < \langle v^2 \rangle$ when there is the absence of gravity [1] or other field

forces. The scale of particle motion is also smaller than λ. However, the diffusivities result from displacements over a long time t, or $\langle v_p^2 \rangle t$ and $\langle v^2 \rangle t$ with $\langle v_p^2 \rangle$ given by Eq. (1). We note that

$$D_p/D \gtrsim \langle v_p^2 \rangle / \langle v^2 \rangle \tag{5}$$

and at large K, Eq. (1) gives $\langle v_p^2 \rangle / \langle v^2 \rangle \simeq (\pi)^{1/2}/K$. Another view is that here the particle intensity is limited by the scale of random motion of the fluid, or $\langle v_p^2 \rangle^{1/2} \lesssim \lambda F$, because the particle cannot be accelerated to a velocity beyond that permitted by the long relaxation time (1/F) and the particle diffusivity $D_p \lesssim (2/(\pi)^{1/2}\lambda\ (\lambda F) \simeq [(\pi)^{1/2}/K]$ at large K, a similar result as in Eq. (5).

For the intermediate range of $\langle v_p^2 \rangle$ given by Eq. (1), and scale limited by λ or R, and $D_p/D \tilde{<} \langle v_p^2 \rangle^{1/2} / \langle v^2 \rangle^{1/2}$ for $R > \lambda$ and

$$D_p/D \simeq \pi^{1/4}/K^{1/2} \tag{6}$$

as an approximation.

Equations (4), (5), and (6) are shown in Fig. 1 together with the theoretical results of Peskin [5] and measurements made on glass particles [1] and coal dusts [6]. In a pipe flow system, Fig. 1 permits an estimation of D_p from D given by [1]:

$$D \simeq (k)\ 2RU \cdot 10^{-3} \tag{7}$$

for k ranging from 0.8 to 5.6 for flow at mean velocity U giving Reynolds numbers $(2RU\bar{\rho}/\bar{\mu})$ ranging from $2 \cdot 10^4$ to $6 \cdot 10^5$.

Note that the above diffusivity relations at small relative motion is applicable to laminar flow where besides Brownian motion, D could be induced by wall interaction (that is, motion induced by the shear layer of the fluid) and perturbation of the flow field by the particle (such as via action and reaction of the wake of a particle [7]). In these situations, D and D_p may become self-consistent, or D may become prominent only in the

vicinity of a particle. This is because in laminar flow of a simple fluid, only molecular diffusivity is active. Presence of particles and their diffusivity may induce additional diffusivity in the fluid phase.

The significance of particle diffusivity in the dynamics of a dilute suspension is seen in that the resistance to the shear motion of a cloud of non-colliding particles corresponds to that of the transport of momentum of particles by their diffusion, or for simple shear flow with velocity gradient of the particle phase $\partial u_p/\partial y$,

$$\tau = \rho_p D_p \partial u_p/\partial y \tag{8}$$

Thus, $\rho_p D_p$ corresponds to the viscosity of the particle phase in the mixture, while the viscosity of the fluid phase in the mixture is nearly $\bar{\mu}$, the viscosity of the material constituting the fluid phase.

Similarly, the thermal conduction by the non-colliding particles corresponds to the transport of the thermal energy of the particles of specifif heat c_p by diffusion or the heat flux due to the gradient of temperature T_p of the particle cloud:

$$J_q = -c_p \rho_p D_p \partial T_p/\partial y \tag{9}$$

Thus, $c_p \rho_p D_p$ corresponds to the thermal conductivity of the particle phase in the mixture while that of the fluid phase in the mixture is nearly $\bar{\kappa}$, the thermal conductivity of the fluid material.

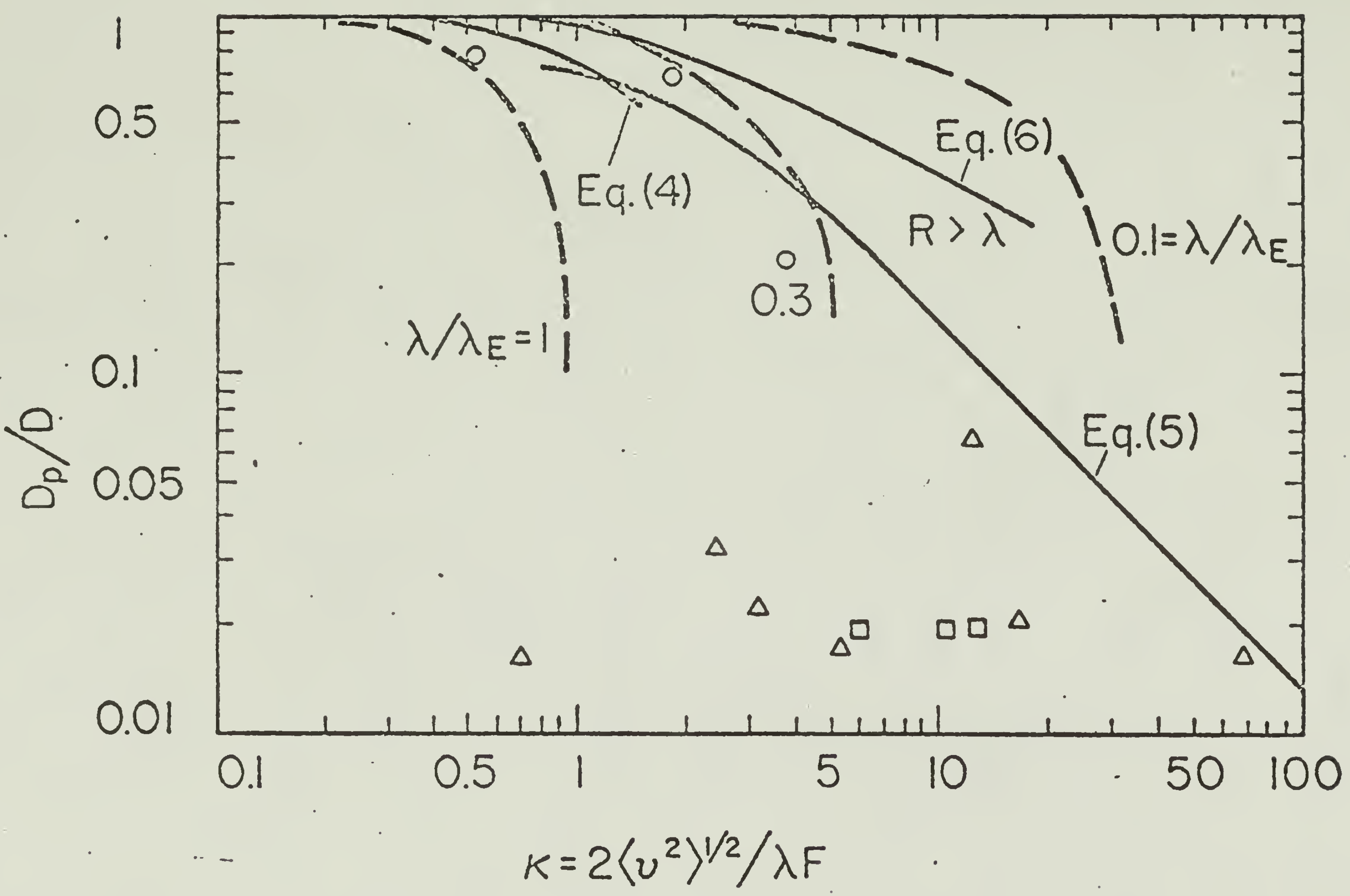

Figure 1 Diffusivity Ratio as a Function of Parameter K (λ

(λ_E is Eulerian Microscale; ○ — from Peskin [5],

□ from Cheng, et al [6]; and

△ from Soo, et al [1]).

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FIGURE CAPTION

Figure 1 Diffusivity Ratio as a Function of Parameter K (λ

(λ_E is Eulerian Microscale; ○ -- from Peskin [5],

□ -- from Cheng, et al [6]; and

△ -- from Soo, et al [1]).

Equation of motion of a solid particle suspended in a fluid

S. L. Soo

Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois
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Consistent approximation calls for taking into consideration the effect of inertia of the fluid in a pressure gradient thus canceling out the term due to static pressure alone. Inconsistency may lead to ill-posed formulations.

When treating the motion of a spherical particle in a fluid, many studies have been made via the formulation by Tchen,[1] who synthesized the relations of Basset, Boussinesq, Stokes, and Oseen. In Eq. (1), the first term on the right-hand side is the viscous resistance due to Stokes, the second term is the force due to the gradient of static pressure in the fluid

$$(4\pi/3)a^3\bar{\rho}_p(dU_p/dt) = 6\pi\mu a(U-U_p) - (4\pi/3)a^3(\partial P/\partial x) + f \quad , \tag{1}$$

nd f includes a force to accelerate the apparent mass of he particle relative to the ambient fluid, that of deviaion in the flow pattern from steady motion, and the exernal force due to potential field.[2] In Eq. (1), a is the adius of the particle, $\bar{\rho}_p$ is the density of the material onstituting the particle, U and U_p are the velocities of he fluid and the particle, respectively, t is the time, is the space coordinate from the fluid stagnation point f the sphere through its center, μ is the viscosity of he fluid, and P is the pressure. a is assumed to be mall. *Equation* (1) *is a relation which holds for small olume fractions of particle matter.*

It is noted that the viscous resistance due to Stokes, $\pi\mu a(U-U_p)$, was computed by neglecting the inertia of he fluid, and the Reynolds number Re given by $a\rho(U-U_p)/\mu$ is smaller than 1. However, the fluid annot sustain the pressure gradient $\partial P/\partial x$ without the nertia effect of the fluid. At a distance ($\gg a$) from the article, even when the motion is steady, we have

$$\rho U(\partial U/\partial x) = -\partial P/\partial x \quad , \tag{2}$$

here ρ is the density of the fluid. In relation to a mall particle whose center is in a plane normal to the irection of fluid motion at velocity U_m a linear approxiation gives

$$U \simeq U_m - (x-a)(\partial P/\partial x)_0/U_m\rho \quad , \tag{3}$$

here $(\partial P/\partial x)_0$ is the local pressure gradient, and the uid velocity varies from the nose to the rear of the here. This fluid velocity can be accounted for in the seen solution[3] for the inertia effect. An approximate olution is available by extending the calculations of rössling[4] whereby we can show that the fraction increase in friction force in a decelerating fluid over a sphere is of the order of $(\partial P/\partial x)_0 a/\rho U_m^2$. This gives a total viscous force of the magnitude

$$6\pi\mu a(U_m - U_p) + (4\pi/3)a^3(\partial P/\partial x)_0[O(\mathrm{Re}^{-1})]$$

instead of the Stokes term in Eq. (1); Re is now defined in terms of U_m. Since the Stokes drag is valid for Re $\simeq[O(1)]$, Eq. (1) takes the form

$$(4\pi/3)a^3\bar{\rho}_p(dU_p/dt) = 6\pi\mu a(U-U_p) + f \quad , \tag{4}$$

for $U = U_m$ by the strict definition. Therefore, the force due to the static pressure gradient is canceled out by the attendant effect of the inertia of the fluid based on a consistent approximation. When a solid particle traverses a shock thickness, dissipation reduces the pressure rise, but the large relative velocity also increases Re.

This reconsideration arose from a query of Trapp[5] as to why the complete set of basic equations of both phases of a monodispersed suspension [two continuity equations and two momentum equations for one-dimensional motion in an incompressible fluid; the momentum equation of the particle cloud has the form of Eq. (1)—Eqs. (9.1) to (9.4) in Soo[6]] appear to be improperly posed because two of the four characteristics are imaginary and there are no stable methods by which the equations can be solved. Yet, the simplified form of these equations for $\bar{\rho}_p \gg \rho$ [such as Eqs. (9.8) and (9.10) in Soo[6]] have real characteristics lines, constituting a well-posed initial value problem. After the terms in Eq. (1) were revised to Eq. (4), however, the basic equations, without being simplified, also became well-posed, even when the fluid was compressible. Terms other than $(\partial P/\partial x)$ do not influence the characteristics in this manner. Revision to Eq. (4) is necessary for the consistency of the approximation as outlined in Ref. 1.

This work was supported in part by the National Science Foundation.

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